CMEDE | CENTER FOR MATERIALS IN EXTREME DYNAMIC ENVIRONMENTS

2016 HIGHLIGHTS

WHAT IS CMEDE?

THE CENTER FOR MATERIALS IN EXTREME DYNAMIC ENVIRONMENTS IS A MULTI-INSTITUTION COLLABORATIVE RESEARCH CENTER LOCATED WITHIN THE HOPKINS EXTREME MATERIALS INSTITUTE AT JOHNS HOPKINS UNIVERSITY.

The Center brings together academia, government, and industry to advance the state of the art for materials in extreme dynamic environments.

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CONSORTIUM MANAGEMENT COMMITTEE

FROM THE CMEDE DIRECTOR:

Welcome to the second edition of the Center for Materials in Extreme Dynamic Environments (CMEDE) highlights. 2016 has been an exciting year for CMEDE! We are continuing our extensive collaborative research activities across all four materials groups: ceramics, composites, metals and polymers. We have made exciting scientific advances, and we continue to develop the future materials-by-design workforce.

This has also been a year of significant events for CMEDE. In January, we hosted the Research Management Board, which led to the renewal of the MEDE program for the next five years. There has been significant Congressional and Department of Defense interest in the program. U.S. Senator Tom Carper visited the Center for Composite Materials at the University of Delaware. The Honorable Stephen Welby, Assistant Secretary of Defense for Research and Engineering, visited with students and toured the facilities at Johns Hopkins University, as did legislative staff from U.S. Representative C.A. Dutch Ruppersberger's office. These visits demonstrate that MEDE research is important both to the Army and to the nation.

I would also like to welcome North Carolina A&T State University and the University of North Carolina at Charlotte to the MEDE consortium. Through ARL's Partnered Research Initiative, these two institutions will enhance our metals processing research and capabilities.

As always, we are thankful for the continued support from the U.S. Army and the Department of Defense, as well as the support from the Enterprise for Multiscale Research of Materials and the partners in the MEDE Collaborative Research Alliance (MEDE CRA), without whom none of this would be possible.

As we move forward into 2017, I am excited to see our advances in developing an integrated, materials-by-design capability transition towards protection materials that benefit the U.S. Army.

K.T. RAMESH

Director, CMEDE

Alonzo G. Decker Jr. Professor of Science and Engineering

Professor, Department of Mechanical Engineering, Earth and Planetary Sciences, Materials Science and Engineering
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Cooperative Agreement Manager
MEDE CRA
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RICHARD HABER

Professor, Materials Science and Engineering
Rutgers University

ABOUT US

In 2010, two National Research Council boards established a committee to examine opportunities in protection materials science and technology for future Army applications. This committee recommended that the Department of Defense establish an initiative for protection materials by design. This initiative would include a combination of computational, experimental, and materials testing, characterization, and processing research to be conducted by academia, government, and industry.

In response to the committee's recommendation, in April 2012 the Army Research Laboratory (ARL) established a framework to integrate the Army's multiscale basic research in materials into one coordinated enterprise. Called the Enterprise for Multiscale Research of Materials (EMRM), the focus of the program is to develop a materials-by-design capability for the U.S. Army using validated multiscale and multidisciplinary modeling capabilities to predict material structure, properties, and performance.

> **Called the Enterprise for Multiscale Research of Materials (EMRM), the focus of the program is to develop a materials-by-design capability for the US Army using validated multiscale and multidisciplinary modeling capabilities to predict material structure, properties, and performance.**

The Enterprise enables ARL to coordinate its in-house activities with extramural research efforts. The EMRM is organized into four major areas: protection materials, energetic materials, electronic materials, and cross-cutting computational science.

To launch the protection materials research component of EMRM, ARL competitively awarded and then signed the Materials in Extreme Dynamic Environments cooperative research agreement with Johns Hopkins University (JHU), the California Institute of Technology (Caltech), the University of Delaware (Delaware) and Rutgers University. The agreement allowed JHU, which is the lead research organization within the consortium of university and research partners, to establish the Center for Materials in Extreme Dynamic

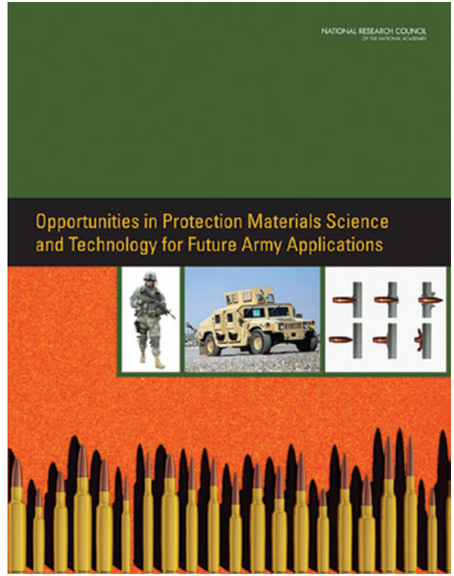


Figure 1: *National Research Council report*

Environments, or CMEDE. CMEDE is a center within the Hopkins Extreme Materials Institute, and focuses on advancing the fundamental understanding of materials in high-stress and high-strain-rate regimes, with the goal of developing a materials-by-design capability for these extreme environments. This 10-year agreement, valued up to $90 million, represents a significant investment and demonstrates the importance of the design of protection materials to the U.S. Army.

The MEDE program also supports the Presidential Materials Genome Initiative (MGI) for Global Competitiveness. Established in June 2011, MGI aims to double the speed at which materials are discovered, developed, and deployed. The MEDE program represents one of the Department of Defense's largest investments in extramural basic research in support of the MGI.

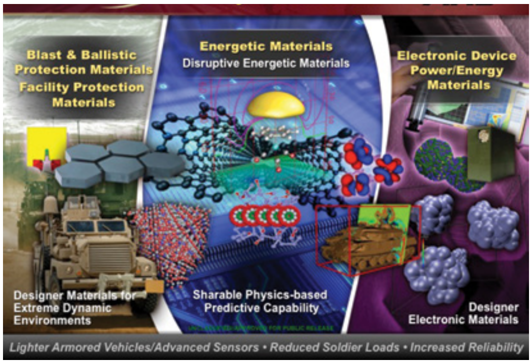


Figure 2: *Army illustration representing the EMRM.*

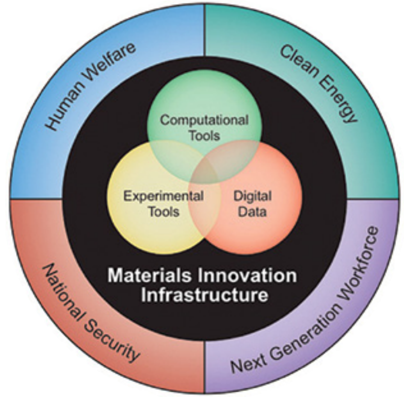


Figure 3: *Materials Genome Initiative: MEDE focuses on developing the experimental and computational tools needed to develop protection materials for national security.*

ORGANIZATION

The MEDE Collaborative Research Alliance (CRA) is composed of a consortium of university and research partners and the Army Research Laboratory. The MEDE consortium members include:

- **Johns Hopkins University (Lead)**
- **California Institute of Technology**
- **University of Delaware**
- **Rutgers University**
- **Drexel University**
- **Ernst Mach Institut**
- **Morgan State University**
- **New Mexico Institute for Mining and Technology**
- **North Carolina Agricultural and Technical State University**
- **Purdue University**
- **Southwest Research Institute**
- **University of North Carolina at Charlotte**
- **University of Texas at San Antonio**
- **Washington State University**

Additionally, through government agreements, the MEDE CRA collaboratively works with the Defence Science and Technology Laboratory of the United Kingdom.

The MEDE CRA is composed of a consortium of university and research partners and the Army Research Laboratory. It also works internationally with the Defence Science and Technology Laboratory of the United Kingdom.

Johns Hopkins University
New Mexico Tech
Science • Engineering • Research • University
Caltech
North Carolina Agricultural and Technical State University
University of Delaware
Purdue University
Rutgers
SwRI
Drexel University
UNC Charlotte
Morgan State University
UTSA
ARL
Washington State University

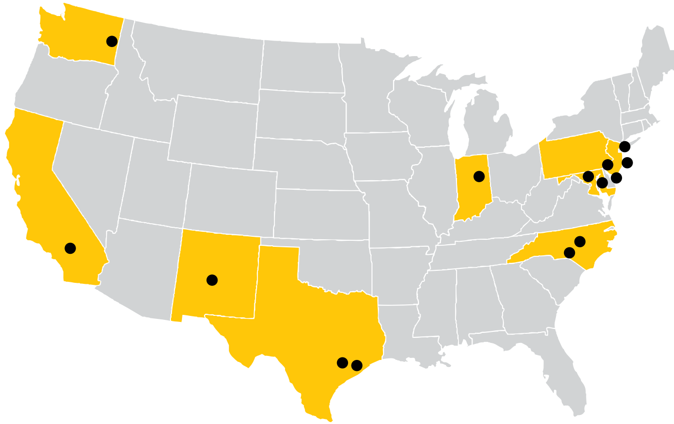


Figure 4: *MEDE Collaborative Research Alliance*

STRUCTURE

- The CMEDE Director is located within CMEDE at Johns Hopkins University, the lead research organization for the MEDE CRA.
- The MEDE Science Advisory Board complements ARL's Technical Advisory Board. It provides important scientific insight, oversight and expertise to the CMEDE consortium. The Board reports to the CMEDE Director.
- The Consortium Management Committee (CMC) is composed of a senior representative from the four major consortium partners and the ARL Cooperative Agreement Manager. The CMC is the final decision authority for the MEDE CRA.
- A Collaborative Materials Research Group (CMRG) coordinates all research activities for each material type. Each CMRG is co-led by a consortium principal investigator and an ARL researcher.
- Within each CMRG are three Collaborative Technical Research Groups (CTRGs): experimental, modeling and processing. Each CTRG is co-led by a consortium principal investigator and an ARL researcher.

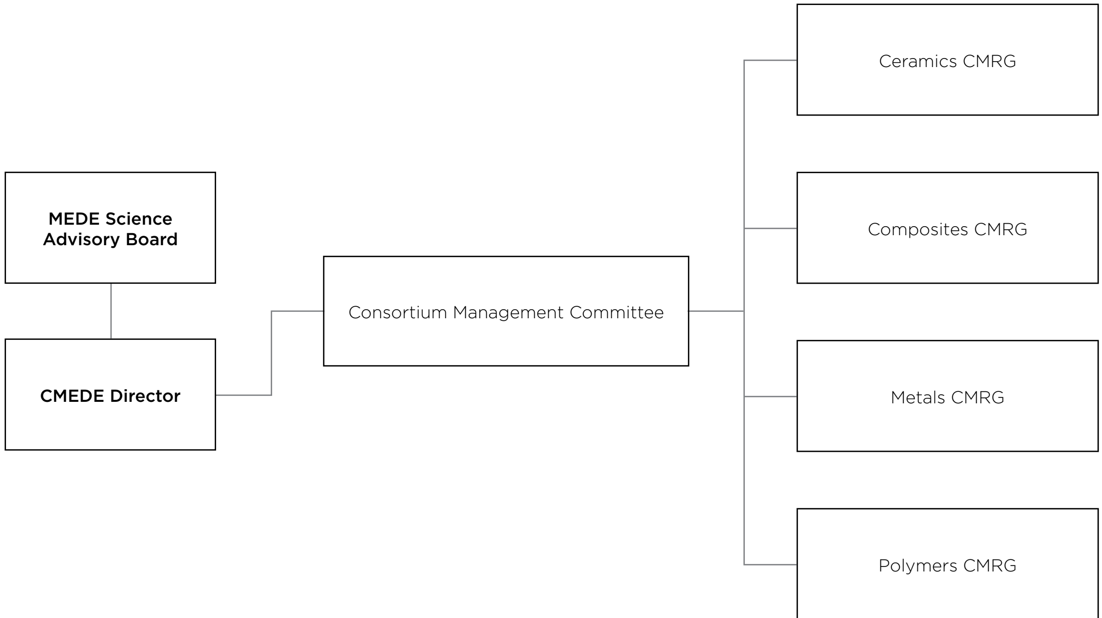


Figure 5: *MEDE organizational structure*

From left: Prof. Rodney Clifton, Dr. Doug Templeton, Dr. Donald Shockey, Prof. Susan Sinnott, Prof. Tony Rollett, Prof. Marc Meyers.
Not shown: Prof. Irene Beyerlein, Prof. Horacio Espinosa, Prof. David McDowell, Prof. Steve McKnight, Prof. Tom Russell, Prof. Nancy Sottos.

MEDE SCIENCE ADVISORY BOARD MEMBERS

Dr. Donald Shockey,
SRI International (Chair)

Professor Irene Beyerlein,
University of California, Santa Barbara

Professor Rodney Clifton,
Brown University

Professor Horacio Espinosa,
Northwestern University

Professor David McDowell,
Georgia Institute of Technology

Professor Steve McKnight,
Virginia Polytechnic Institute

Professor Marc Meyers,
University of California, San Diego

Professor Anthony Rollett,
Carnegie Mellon University

Professor Thomas Russell,
University of Massachusetts Amherst

Professor Nancy Sottos,
University of Illinois at Urbana-Champaign

Professor Susan Sinnott,
Pennsylvania State University

Dr. Douglas Templeton,
DWT Consulting

RESEARCH STRATEGY

The objective of the MEDE program is to develop the technical and workforce capability to design, create, and optimize novel material systems that exhibit revolutionary performance in extreme dynamic environments. Achieving this objective requires a new paradigm for materials research and workforce development. One cannot use the classical materials science structure-properties-performance approach because path-dependent and time-dependent failure processes are involved in these dynamic environments, and optimal solutions may not exist in the traditional design space. Instead, we must design with knowledge of the dynamic failure processes (mechanisms) that are involved in the actual application.

The objective is not necessarily to produce a specific material system that is optimized for a specific range of applications, but rather to produce a way of thinking that will allow the design of lightweight protective material systems that can be used for extreme dynamic environments.

To achieve the MEDE program objectives, research activities are focused on a materials-by-design process involving a canonical model and a mechanism-based strategy as shown in Figure 6. We have established a canonical model for each model material under investigation. A canonical model is defined as: "A simplified description of the system or process, accepted as being accurate and authoritative, and developed to assist calculations and predictions."

Typically such a canonical model defines key variables and their ranges, defines critical mechanisms, and then prioritizes the variables and mechanisms. Beginning with a canonical model allows a large group of researchers to ensure that efforts are relevant in terms of both science and application.

Once the canonical description is established, researchers can then proceed with the mechanism-based strategy. Researchers seek to see the mechanisms during the extreme dynamic event, to understand them through multiscale models, and to control them through synthesis and processing. Understanding the mechanisms through multiscale models provides the capability to define integrative experiments and to test the coupling of mechanisms. This information leads to validated models and codes, which feed back into the canonical model, by transitioning into Department of Defense (DoD) and Department of Energy (DoE) codes. Similarly, controlling the mechanism through synthesis and processing leads to newly designed materials for the canonical environment. Industry helps to determine the scale-up feasibility of these newly designed materials, which are then fed back to the experiments in the canonical modeling effort.

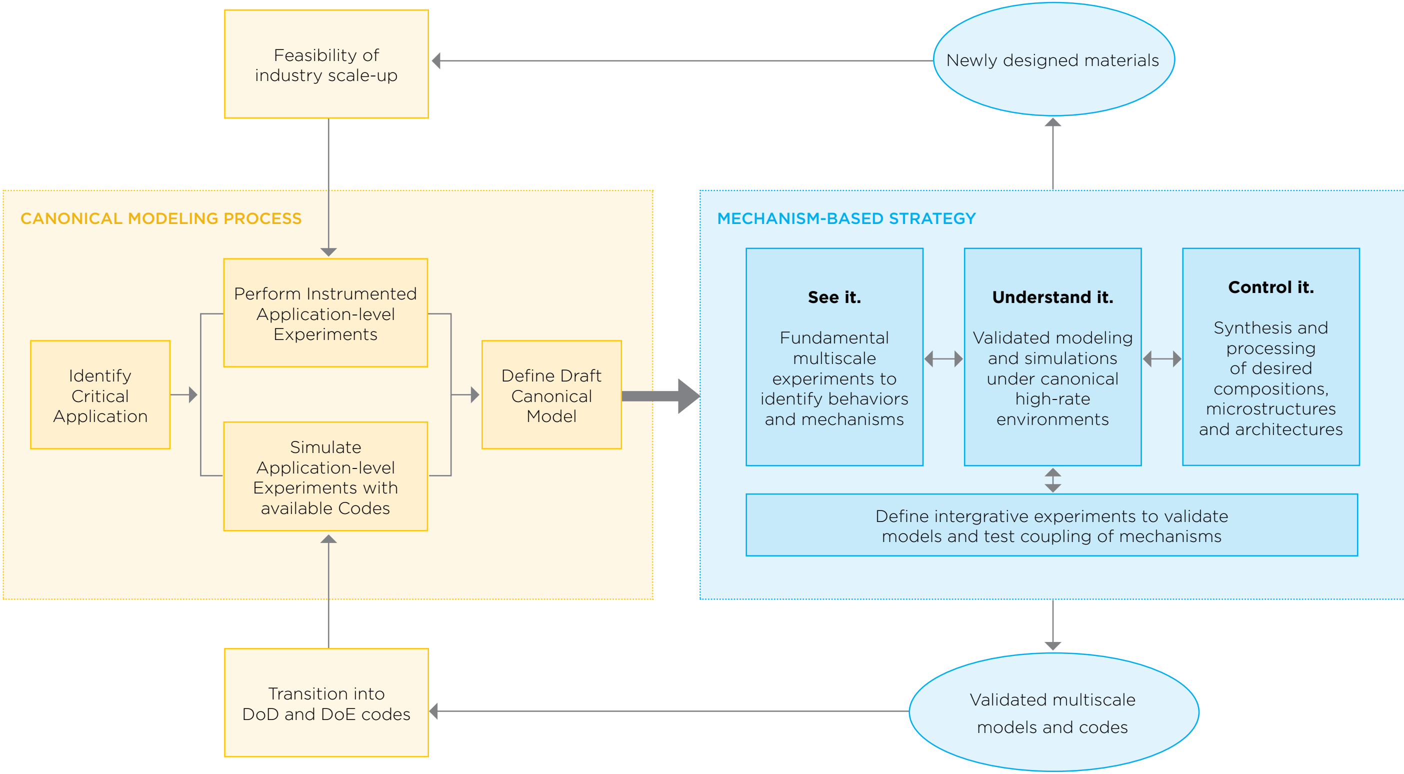


Figure 6: *Overall design strategy for protection materials. Left hand boxes are driven by ARL, while right hand boxes are driven by the MEDE Consortium.*

RESEARCH ACTIVITIES

Currently the MEDE program examines one model material in each of the following four material classes: ceramics, composites, metals, and polymers. The discoveries and insights developed can be used for other materials in the same class.

Ceramics: Boron Carbide

Boron carbide is the model material for the Ceramics CMRG because it has the unrealized potential of dramatic improvements in ballistic performance for vehicular protection at very low weight. The Ceramics CMRG seeks to understand and control the dynamic failure processes in this protective ceramic material and to improve its dynamic performance by controlling mechanisms at the atomic and microstructural levels through multiscale modeling, advanced powder synthesis, control of polytypes, and microstructural improvements.

Application: Boron carbide is one of the component materials used to protect soldiers and military vehicles from blast and ballistic threats.

Composites: S-2 Glass/Epoxy Interface

Composite materials subjected to dynamic loads are essential examples of high performance systems in the conventional sense. In order to focus on the complexities raised by the interfaces and architectures, S-2 Glass/Epoxy is the model system for the Composites CMRG. The Composites CMRG develops the fundamental understanding of the role of interfaces, component interactions, and composite architecture over the full range of length scales and time scales that are manifested in the system during the dynamic event.

Application: S-2 Glass/Epoxy provides a strong, structural backing system to support protective plates for military vehicles.


Photo: Jay Gould, MICA

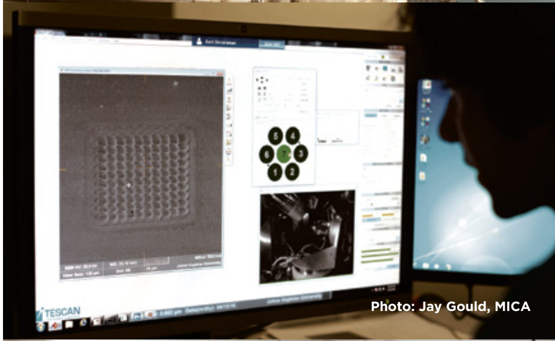


Photo: Jay Gould, MICA

Photo: Will Kirk, Homewood Photography

Metals: Magnesium

The magnesium alloy system is the model material for the Metals CMRG because it is the lightest-weight structural metal that offers the potential of approaching steel-like ballistic performance while using conventional low-cost and time-tested processing techniques. We are enhancing the dynamic performance of this hexagonally-close-packed metal using experimentally validated modeling and alloy design to control dynamic strengthening and failure mechanisms, including deformation twinning.

Application: The U.S. Army's Stryker vehicle incorporates magnesium in its structure. In comparison to steel, magnesium offers the potential for a lightweight metal system that could enhance the deployability and protection of military vehicles.

Polymers: UHMWPE

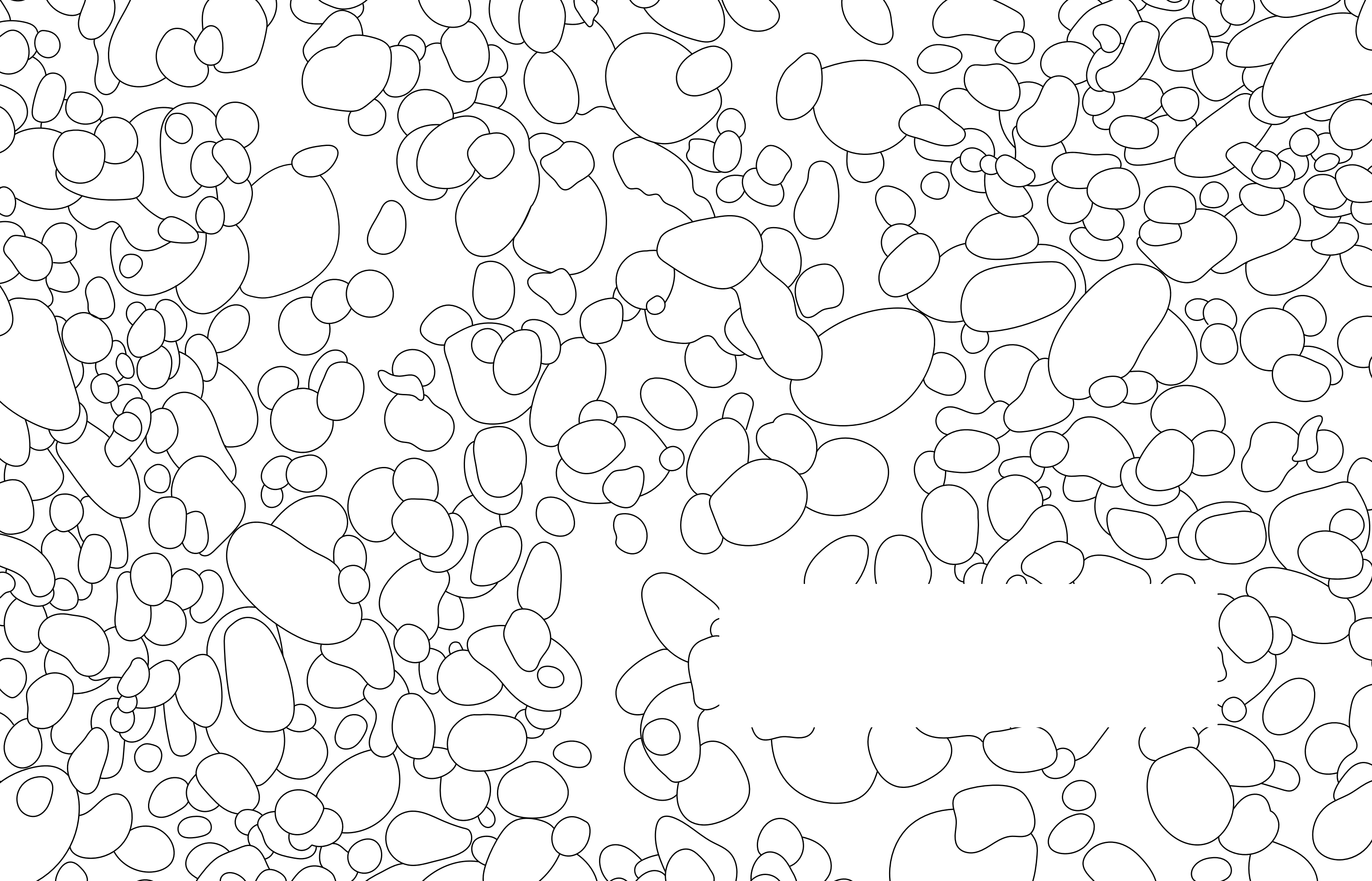
Polyethylene is the model system for the Polymers CMRG because of the potential for significant improvement in its mechanical properties. Ultra High Molecular Weight Polyethylene (UHMWPE) is used in a wide variety of military applications in both tape and fiber forms, but its tensile strength remains an order of magnitude below the theoretical value. The Polymers CMRG seeks to determine the roles of atomic scale defects, chain length, degree and length scale of crystallinity in determining and limiting the mechanical response under extreme dynamic conditions.

Application: UHMWPE shows tremendous promise for the next generation of helmets and body protection for soldiers.

CMEDE RESEARCH ACTIVITIES ADDRESS THE FOLLOWING FIVE CORE ELEMENTS:

- **Advanced Experimental Techniques:** developing experimental methodologies to interrogate and characterize the in-situ materials response to extreme dynamic environments at critical length and time scales.
- **Modeling and Simulation:** developing computational approaches to predict the materials response to extreme dynamic environments at critical length and time scales.
- **Bridging the Scales:** developing physical and mathematical constructs necessary to bridge critical length and time scales.
- **Material Characteristics and Properties at Multiple Scales:** utilize existing and novel experimental methodologies to identify the comprehensive set of material characteristics, microstructural features, and dynamic properties that govern high rate deformation and failure phenomena, and to validate computational approaches in order to bridge the characteristic length and time scales.
- **Synthesis and Processing:** incorporate research discoveries to enable the synthesis of novel materials and the processing of final products with critical material characteristics and resulting properties.

Artistic rendering of the atomic-level view of boron carbide as seen through a transmission electron microscope.



CERAMICS

Consortium Lead - Prof. Richard Haber (Rutgers)

ARL Lead - Dr. Jerry LaSalvia

Ceramics CMRG

CONSORTIUM PRINCIPAL INVESTIGATORS

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Dr. Vladislav Domnich, Rutgers

Prof. William Goddard, Caltech

Prof. Lori Graham-Brady, JHU

Prof. Rich Haber, Rutgers

Prof. Kevin Hemker, JHU

Prof. Todd Hufnagel, JHU

Prof. K.T. Ramesh, JHU

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Dr. Shawn Coleman

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Dr. Efrain Hernandez

Dr. Sergiy Izvyekov

Dr. Jerry LaSalvia

Mr. Brian Leavy

Dr. Jonathan Ligda

Dr. James McCauley

Dr. Jason McDonald

Dr. Chris Meredith

Dr. Sikhanda Satapathy

Dr. Brian Schuster

Dr. JP Singh

Dr. Jeffrey Swab

Dr. Jennifer Synowczynski-Dunn

Dr. DeCarlos Taylor

Dr. Andrew Tonge

Dr. Mark Tschopp

Dr. Scott Walck

CONSORTIUM RESEARCH TASKS

- Characterization of Deformation Mechanisms and Amorphization in Boron Carbide (Haber and Domnich, Rutgers)
- Characterization of Defects and In Situ Visualization of Fracture in Boron Carbide (Hufnagel and Ramesh, JHU)
- Control of Inelastic Mechanisms in Boron Carbide Through Processing (Haber, Rutgers)
- Crack Coalescence, Comminution and Granular Flow of Highly Damages Ceramics (Graham-Brady and Ramesh, JHU)
- Extension of the First Principles Based ReaxFF Multiscale Simulation Technology Developed in MEDE-I to Full Scale Multigrain and Microalloying to Optimize Strength and Ductility in MEDE-II (Goddard, Caltech)
- High-Rate Characterization, Granular Flow and Amorphization in Boron Carbide Materials (Ramesh, JHU)
- Multiscale Physics-based Modeling for Dynamic Deformation and Dynamic Failure of Advanced Ceramics (Daphalapurkar, JHU)
- TEM and APT Characterization of Boron Carbide (Hemker, JHU)

Control of Inelastic Mechanisms in Boron Carbide Through Processing: High Temperature Coupling of B_4C and SiB_6 for Diffusion Mapping and Mechanical Testing

Professor Richard Haber
Rutgers University

Dr. Vladislav Domnich
Rutgers University

Dr. Kelvin Xie
Johns Hopkins University

Mr. Anthony Etzold
Rutgers University

In the development of armor ceramics, the modification of currently existing materials can lead to enhanced characteristics while maintaining the serviceability of current processing infrastructure. We have long been enhancing the processing and development of boron carbide, B_4C, which is well known as an extremely hard material with low density and exceptional resistance to wear. Using Rutgers' rapid carbothermal reduction synthesis for boron carbide production has led to a decreased reaction time, a controlled stoichiometry, decreased particle size, and allows for the elimination of free carbon in the final product. This final powder can then be sintered without further processing due to its already small particle size and leads to a maximization of desired properties. However, while boron carbide has many ideal properties, the need for modification stems from both its brittle nature and its low fracture toughness.

Recent work done at Rutgers University has begun introducing silicon into the boron carbide lattice in an attempt to enhance the toughness of the material. By coupling boron carbide with a boron silicide at high temperature for extended timeframes, we have been able to map the diffusion of silicon into boron carbide and observe this material at varying silicon levels along the diffusion zone using Energy Dispersive X-ray Spectroscopy. With the diffusion of silicon mapped, Dr. Domnich, using nano-indentation along with Raman Spectroscopy, was able to determine the changes in amorphization in the varying stoichiometries of the Si-BC material. Using X-ray diffraction at Rutgers, we are able to determine the location of silicon within the boron carbide lattice and along with TEM by Dr. Xie at Johns Hopkins we will be able to confirm our observations and begin to understand the effect silicon introduction has on other components of the microstructure of the boron carbide.

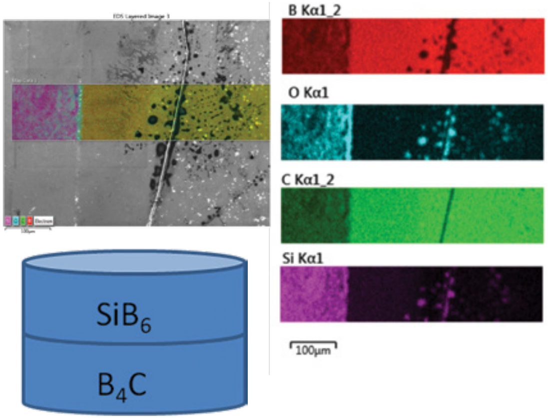


Figure 7: *Energy Dispersive X-ray Spectroscopy map showing the movement of silicon into boron carbide.*

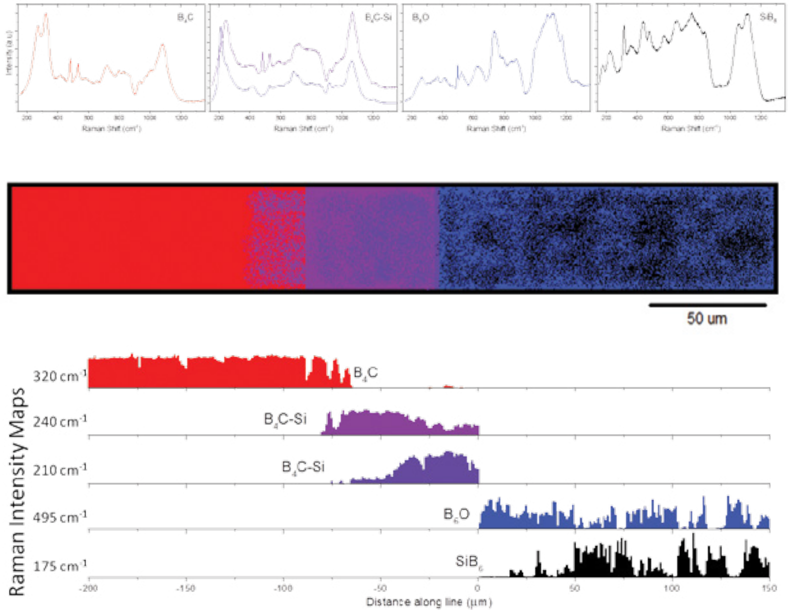


Figure 8: *Raman analysis showing phase transition of boron carbide within the diffusion zone.*

DR. KANAK KUWELKAR

R&D Scientist at Daramic LLC, earned doctorate while serving as Graduate Research Assistant at Rutgers University

MEDE Area of Research:
Characterization of Boron Carbide Powders and Boron Carbide Ceramics

> "Working as part of the MEDE program gave me the opportunity to routinely collaborate with researchers from the MEDE consortium, which included members from ARL, JHU, DSTL and Caltech. The biweekly meetings encouraged open forum discussions and technology exchange, which provided me with the tools to address key problems impacting the boron carbide community. Through this program, I was able to develop my skills as a Materials Scientist, ensuring that I was ready for the industry after graduation. The highlight of my time in the MEDE program was my visit to DSTL in England, where I interacted with our European counterparts working on Materials in Extreme Dynamic Environments."

DR. VLADISLAV DOMNICH

Research Associate, Rutgers University

MEDE Area of Research:
Characterization of Deformation Mechanisms and Amorphization in Boron Carbide and CerPro1: Control of Inelastic Mechanisms in Boron Carbide through Processing

"Being part of a multi-discipline and highly engaged research team effort aimed at the development of novel classes of protection materials has been the most exciting aspect of the MEDE program. Through active collaboration with the research groups at the Army Research Laboratory and partner educational institutions, procedures and methods are being developed for producing currently unattainable ceramic materials that are microstructurally engineered across the length scales (atomistic to micro) and are characterized by improved hardness, toughness, inelastic behavior, and chemical inertness."

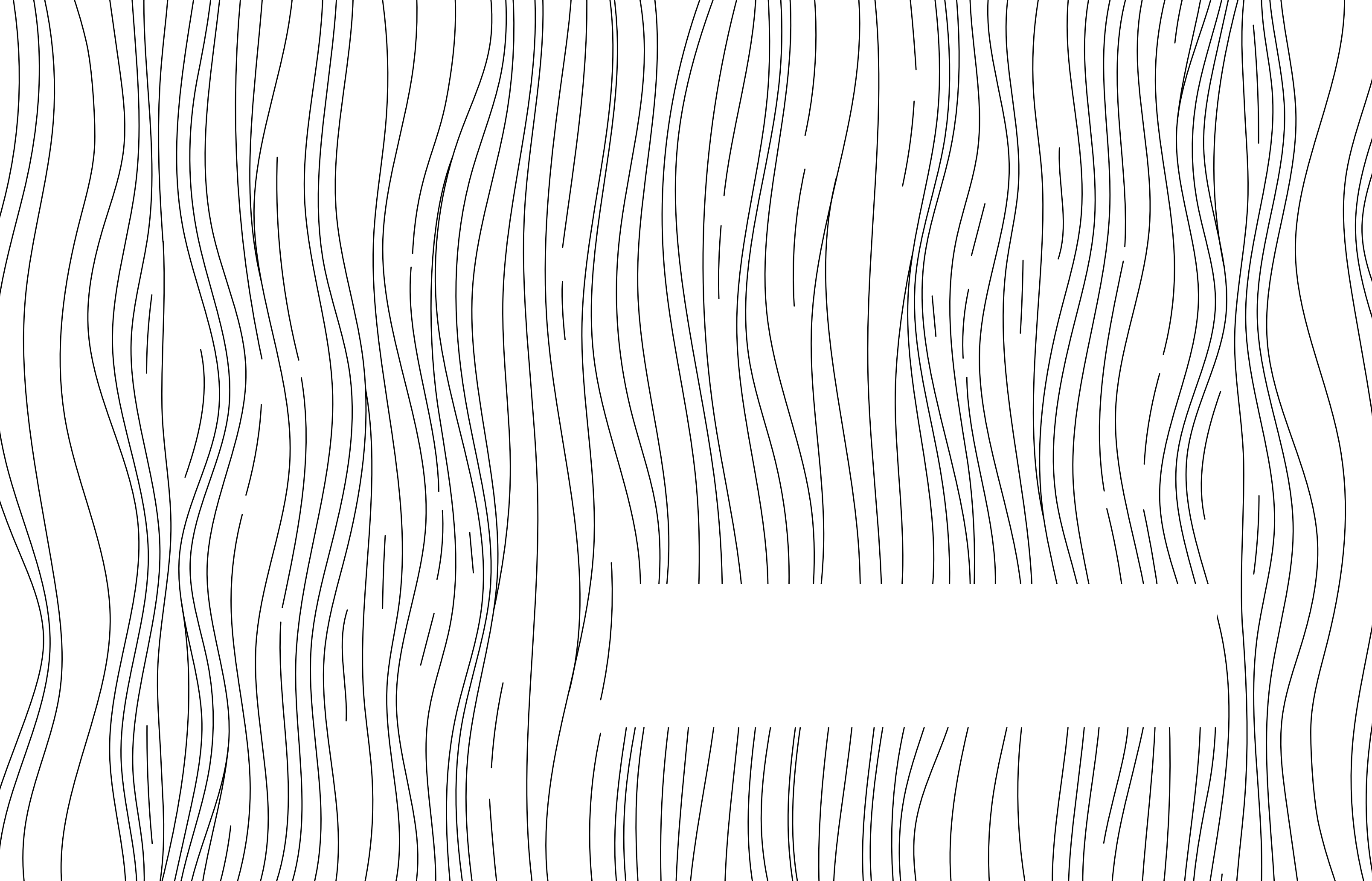
DR. BRADY AYDELOTTE

Mechanical Engineer, U.S. Army Research Laboratory

MEDE Area of Research:
Canonical Model for Boron Carbide

"The MEDE program supports in-depth, scientific study of the behavior and performance of important materials and material systems used in body armor or other military equipment. By understanding the underlying physical behavior of important materials in conditions relevant to combat use, it becomes possible to improve material performance and deliver better equipment to soldiers. These improvements enhance their safety and combat effectiveness."

Artistic rendering of a cross-section of the S-2 Glass/Epoxy composite material.



COMPOSITES

Consortium Lead - Prof. John W. Gillespie, Jr. (Delaware)

ARL Lead - Dr. Daniel J. O'Brien

Composites CMRG

CONSORTIUM PRINCIPAL INVESTIGATORS

Prof. Cameron Abrams, Drexel

Prof. Suresh Advani, Delaware

Prof. Kadir Aslan, Morgan State

Prof. Wayne Chen, Purdue

Dr. Sanjib Chowdhury, Delaware

Prof. Somnath Ghosh, JHU

Prof. John W. Gillespie, Jr., Delaware

Prof. Lori Graham-Brady, JHU

Prof. Bazle Haque, Delaware

Prof. Giuseppe Palmese, Drexel

Prof. Shridhar Yarlagadda, Delaware

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Dr. Travis Bogetti

Dr. Robert Elder

Dr. Joe Lenhart

Dr. Kevin Masser

Mr. Chris Meyer

Dr. Daniel J. O'Brien

Dr. James Sands

Dr. Timothy Sirk

Dr. Tusit Weerasooriya

Dr. Chian Fong Yen

CONSORTIUM RESEARCH TASKS

- Characterization of Composite Materials (Aslan, Morgan State)
- Epoxy Molecular Simulations (Abrams and Palmese, Drexel)
- High Rate Test Methods for Interphase Characterization (Gillespie and Haque, Delaware)
- High Strain Fiber-matrix Interfacial Traction Laws (Gillespie and Haque, Delaware)
- Meso-Mechanical Modeling of Canonical Perforation Experiments Laws (Haque and Gillespie, Delaware)
- Micromechanical FE Modeling of Tensile Failure of Unidirectional Composites (Gillespie, Delaware)
- Micro-Mechanical Modeling of Progressive Punch-Shear Behavior of Uni-Directional Composites Laws (Gillespie and Haque, Delaware)
- Multi-scale Modeling of Damage and Failure in Composites (Ghosh, JHU)
- Multi-scale Modeling of Fiber-Matrix Interphase (Gillespie and Chowdhury, Delaware)
- Real-time Damage Visualization in Polymers and Composites (Chen, Purdue)
- Synthesis and Characterization of Interphases and Tows with Controlled Resin Distribution (Advani and Yarlagadda, Delaware)
- Synthesis of Epoxy Networks and Interphases with Controlled Topology (Palmese and Abrams, Drexel)

Real Time Visualization of Dynamic Damage in Composites

Professor Wayne Chen	Professor John W. Gillespie, Jr.	Dr. Daniel J. O'Brien
Purdue University	*University of Delaware*	*U.S. Army Research Laboratory*

Dr. Matt Hudspeth	Mr. Stephen Levine	Mr. Sandeep Tamrakar	Ms. Jocelyn Chu
Sandia National Lab	*Raytheon Missile Systems*	*University of Delaware*	*Purdue University*

We developed novel experimental methods to visualize the dynamic damage initiation and propagation in composite materials in real time. We utilized synchrotron X-ray at Argonne's Advanced Photon Source (APS) as the illumination source and the high-speed imaging capabilities available at APS Beamline 32 ID-B to capture X-ray images and X-ray diffraction patterns simultaneously at millions of frames per second.

The specimens were loaded by either Kolsky bars or a gas gun. We have utilized the new experimental methods to study the dynamic debonding between a fiber and resin. The loading was applied both perpendicular to the fiber direction (cruciform specimen) and along the fiber (droplet specimen) to investigate dynamic debonding in both normal and shear modes.

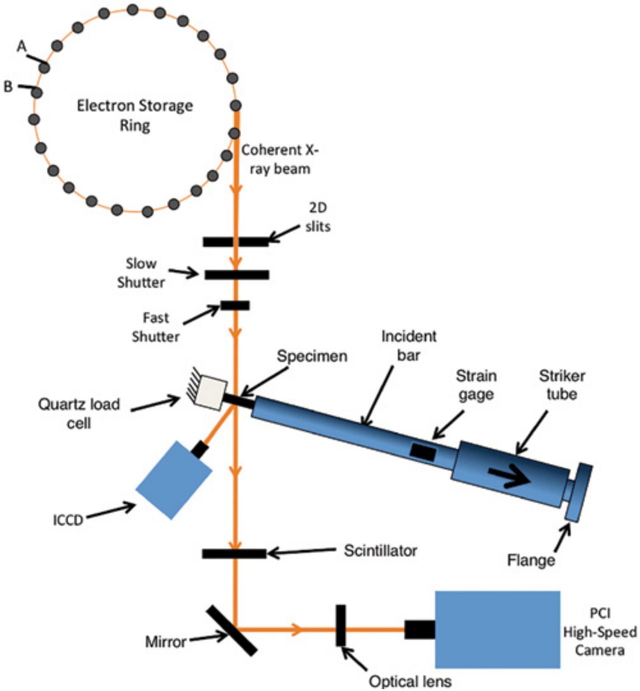


Figure 9: *Schematic of experimental setup*

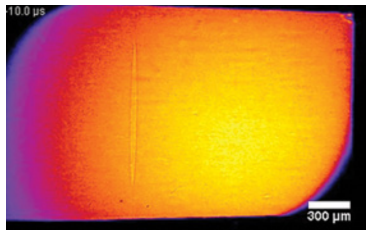


Figure 10: *Dynamic normal debonding*

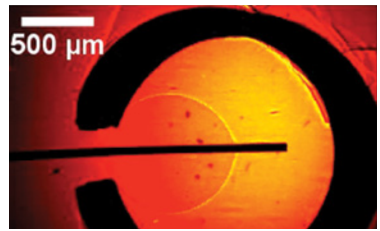


Figure 11: *Dynamic shear debonding*

Multi-scale Modeling of Damage and Failure in Polymer Matrix Composites

Professor Somnath Ghosh
Johns Hopkins University

Dr. Daniel J. O'Brien
U.S. Army Research Laboratory

Mr. Nebiyou Getinet
U.S. Army Research Laboratory

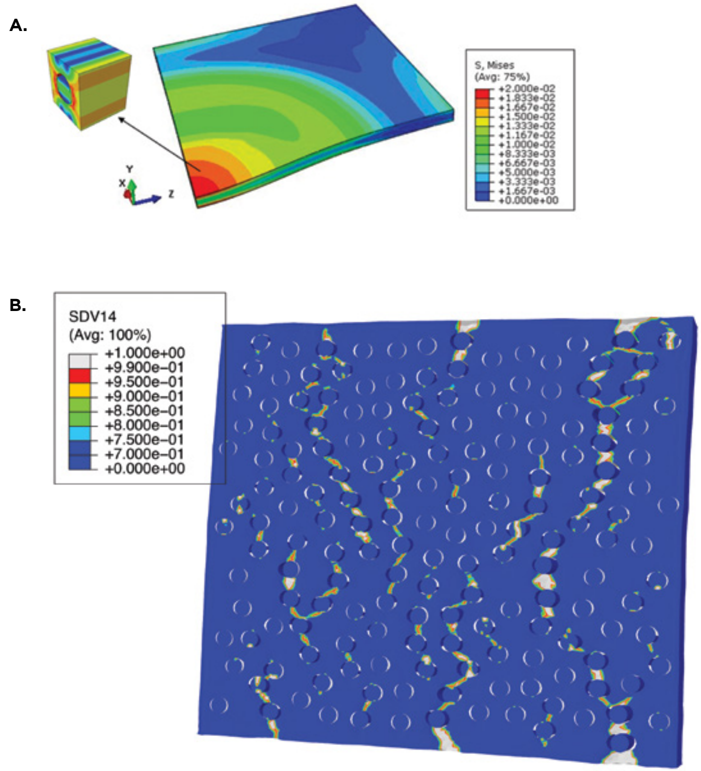
Ms. Zhiye Li
Johns Hopkins University

Mr. Xiaofan Zhang
Johns Hopkins University

Hierarchical multi-scale modeling necessitates the development of parametrically homogenized constitutive models that account for morphological features of the microstructure and explicitly represent the microstructural material behavior and damage evolution [2,3]. This research is developing powerful reduced order constitutive-damage models for polymer matrix composites that can be incorporated in any commercial finite element code such as ABAQUS or LS-DYNA for structural analysis. The resulting parametrically homogenized constitutive models (PHCDM), when incorporated in finite element models of structural failure, significantly enhance the efficiency of computational analysis [3,4].

Hierarchical multi-scaling starts with detailed microscale models of deformation and damage, with explicit representation of the microstructural morphology. An experimentally calibrated and validated 3D finite element model has been developed for simulating strain-rate dependent deformation and damage behavior in representative volume elements of S-glass fiber reinforced epoxy-matrix composites [1,5]. The fiber and matrix phases in the model are assumed to be elastic with their interfaces represented by potential-based and non-potential, rate-dependent cohesive zone models. Damage, leading to failure, in the fiber and matrix phases is modeled by a rate-dependent non-local scalar continuum damage mechanics model (see figure 12). A limited number of validation tests are conducted with cruciform and droplet specimens to characterize interfacial damage behavior. Results of micro-mechanical analysis are homogenized to develop a parametrically homogenized continuum damage mechanics (PHCDM) model with a 4th order tensorial internal variable. The model can also reproduce the detailed micromechanical failure behavior at any location of the structure at a small fraction of the computational cost. The research will provide a platform for using a large-scale simulation-based technology to rapidly develop advanced composites for meeting national security mission needs.

Figure 12: *(a) Contour plot showing the path crack propagation in a multiple fiber, polymer matrix representative volume element, under a uniaxial macroscopic rates of deformation, (b) Stress contour in a composite plate generated by the PHCDM model and the corresponding microscopic stress in a RVE showing failure behavior.*



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2. S. Ghosh, "Foundational aspects of a multi-scale modeling framework for composite materials", Integrating Materials and Manufacturing Innovation, Vol. 4.1 (2015): 1.

3. X. Zhang and S. Ghosh, "Parametric homogenization-based anisotropic continuum damage models for polymer matrix composites", (to be submitted.)

4. X. Zhang, Z. Li, S. Ghosh and D. J. O'Brien, "Parametric Homogenization Based Continuum Damage Mechanics Model for Composites", Proceedings of the American Society for Composites Technical Conference and ASTM Committee D30 Meeting, Williamsburg, Virginia 2016

5. Z. Li, X. Zhang, S. Ghosh, D. J. O'Brien, "Multi-Scale Modeling of Damage and Failure in Borosilicate-glass/epoxy Fiber Reinforced Composite Subject to High Strain Rates" EMI 2016 Conference & Probabilistic Mechanics & Reliability 2016 Conference, May 22-25, 2016.

MR. MICHAEL YEAGER

Graduate Student, University of Delaware

MEDE Task:

Synthesis and Characterization of Model Interphases and Tows with Controlled Resin Distribution

> "MEDE has afforded me the opportunity to explore an interesting research area with a meaningful end goal of making our soldiers safer. It has also provided a forum to present my research to diverse audiences, which increases the rate at which my findings are disseminated."

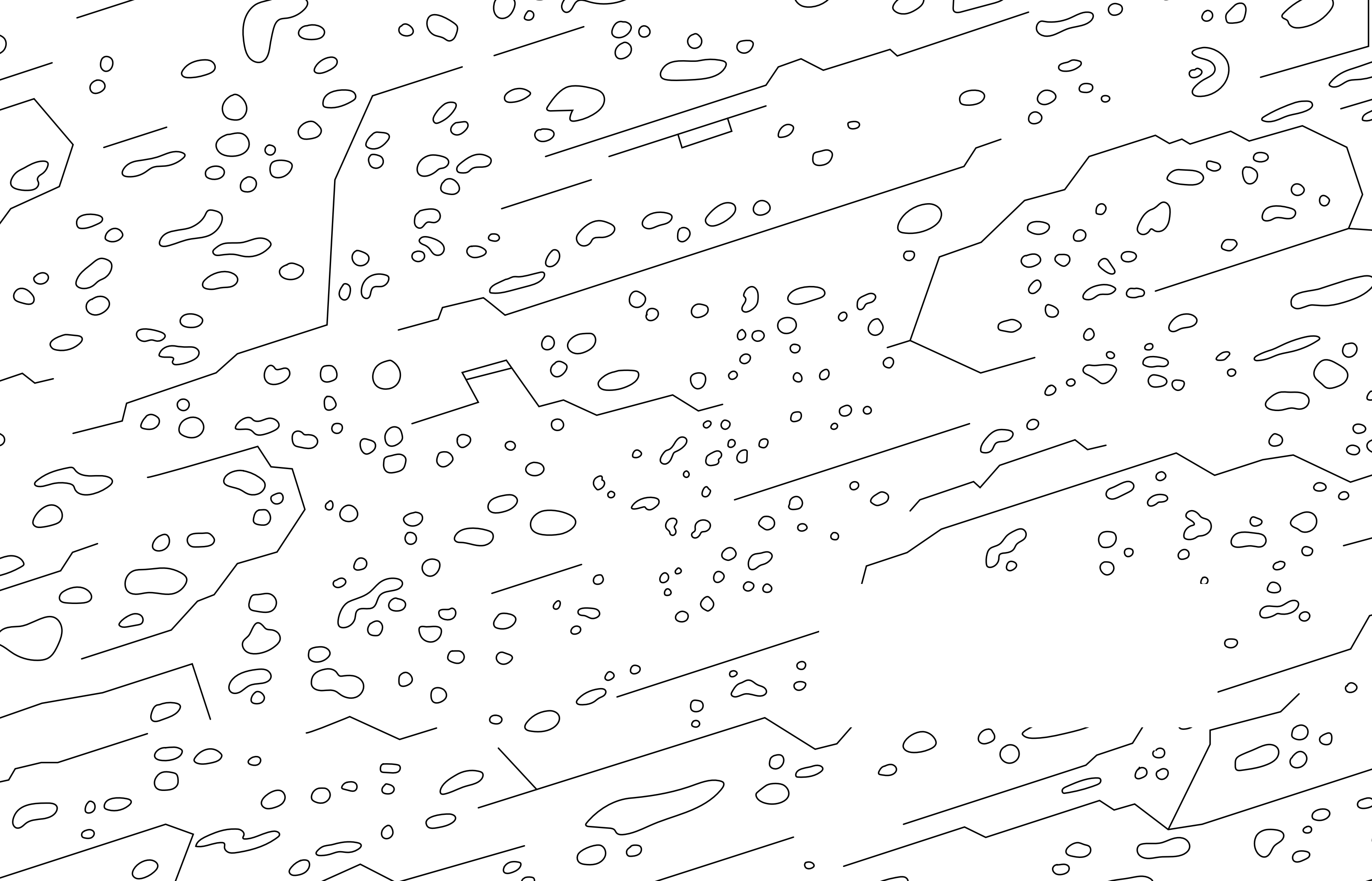
MR. CHRISTOPHER S. "CHRIS" MEYER

Mechanical Engineer, U.S. Army Research Laboratory and Graduate Student, University of Delaware (UD), Center for Composite Materials (CCM) advised by Professor John W. Gillespie, Jr. and Professor Bazle Haque.

MEDE Area of Research:
Meso-Mechanical Modeling of Composite Materials

"The research conducted within the MEDE program requires considerable collaboration and, as both an ARL researcher and a UD graduate student, I have experienced firsthand how it crosses disciplines and institutions. Without the collaborative structure and nature of the program, I would not have had the opportunity to research the responses of mesoscale mechanisms to dynamic insult with members from the University of Delaware, U.S. Army Research Laboratory, Morgan State University, Johns Hopkins University, and Drexel University."

Artistic rendering of magnesium as seen through a transmission electron microscope.



METALS

Consortium Lead - Prof. Tim Weihs (JHU)

ARL Lead - Dr. Laszlo Kecskes

Metals CMRG

CONSORTIUM PRINCIPAL INVESTIGATORS

Prof. Kaushik Bhattacharya, Caltech

Prof. Jaafar El-Awady, JHU

Prof. Yogendra Gupta, WSU

Prof. Todd Hufnagel, JHU

Prof. Jamie Kimberley, NMT

Prof. Dennis Kochmann, Caltech

Prof. Michael Ortiz, Caltech

Prof. Guruswami Ravichandran, Caltech

Prof. K.T. Ramesh, JHU

Prof. Jagannathan Sankar, NC A&T

Prof. Qiuming Wei, UNCC

Prof. Tim Weihs, JHU

Prof. Justin Wilkerson, UTSA

Dr. Zhigang Xu, NC A&T

Dr. Sergey Yarmolenko, NC A&T

CONSORTIUM RESEARCH GROUPS

- Defects Properties Within a Grain (Bhattacharya and Oritz, Caltech; Gupta, WSU; El-Awady, JHU)
- Plasticity Across Multiple Grains (Hufnagel, Ramesh and Weihs, JHU; Ravichandran, Kochmann and Bhattacharya, Caltech; Kimberley, NMT)
- Thermal Mechanical Processing (Weihs and Hufnagel, JHU; Kochmann and Bhattacharya, Caltech)
- Void Dominated Failure (Ortiz and Bhattacharya, Caltech; Wilkerson, UTSA; Weihs, JHU)

ARL COLLABORATORS

Dr. Richard Becker

Dr. Todd Bjerke

Mr. Brady Butler

Dr. Daniel Casem

Dr. John Clayton

Dr. Robert Elder

Dr. Vince Hammond

Dr. Efrain Hernandez

Mr. Tyrone Jones

Dr. Laszlo Kecskes

Dr. Krista Limmer

Dr. Jeffery Lloyd

Dr. Christopher Meredith

Dr. Tomoko Sano

Dr. Scott Schoenfeld

Dr. Brian Schuster

Dr. Mark Tschopp

Dr. N. Scott Weingarten

Dr. Cyril Williams

Unraveling the Competition between Slip and Twinning in Magnesium Microcrystals: Discrete Dislocation Dynamics Simulations

Professor Jaafar A. El-Awady
Johns Hopkins University

Dr. Haidong Fan
Johns Hopkins University

Dr. Sylvie Aubry
Lawrence Livermore National Laboratory

Dr. Athanasios Arsenlis
Lawrence Livermore National Laboratory

We have developed a new coarse-grained simulation methodology to model the interactions between dislocations and twins in magnesium. In this methodology, a systematic interaction model between dislocations and twin boundaries (TBs) was introduced into three-dimensional discrete dislocation dynamics simulations. This interaction model is based on geometric considerations of the hexagonal-closed-packed crystal structure of magnesium as well as detailed atomistic simulations of the dissociation of a dislocation into residual and twinning dislocations at the TB. The model has also been validated through comparisons with various high-resolution transmission electron microscopy experimental observations.

This new methodology provides an avenue to model both dislocation and twinning mediated plasticity in a way that greatly mitigates both the time-scale and length-scale limitations of atomic simulations, and unlike continuum mechanics models (e.g. crystal plasticity), it can quantify mechanisms that control micro-scale plasticity in a physics-based framework with minimal ad hoc assumptions.

This model has been utilized to study the hardening response of twinned polycrystalline magnesium, twin-size effects, and the competition between dislocation slip and twinning as a function of grain size. In the latter, it was shown that twinning deformation exhibits a stronger grain-size effect than that for dislocation mediated slip. This leads to a critical grain size above which twinning dominates, and below which dislocation slip dominates. The results of these simulations will be up-scaled into continuum models through developing microstructurally-based constitutive rules that capture the evolution of deformation to better predict damage and failure in magnesium.

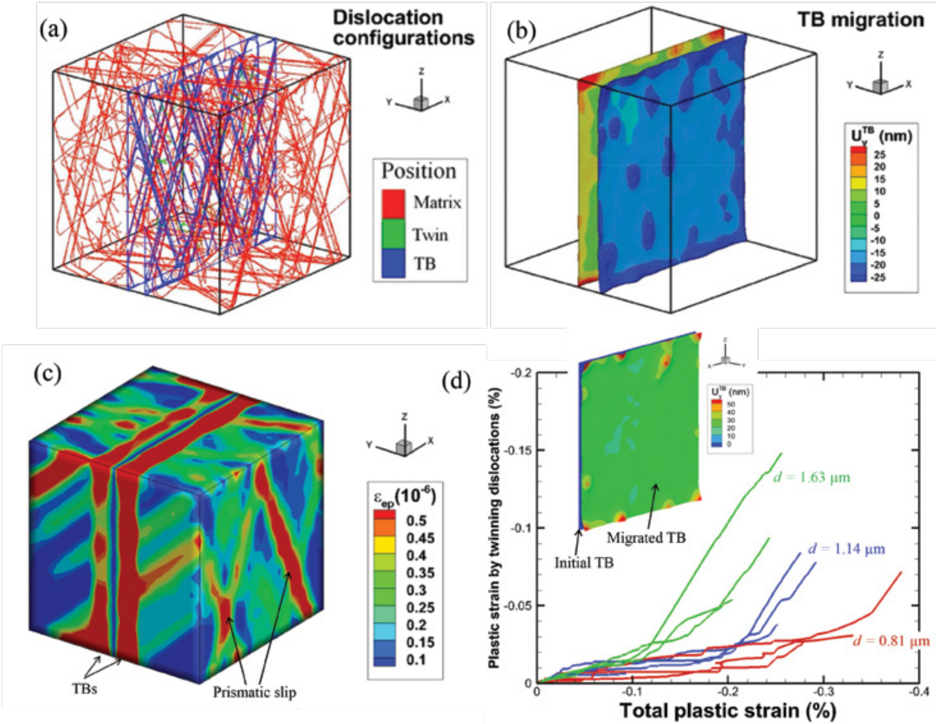


Figure 13: *(a) Dislocation microstructure configuration; (b) Displacement contours on the evolved twin boundaries; and (c) Contours of the effective plastic strain in a 3.0μm twinned grain after 0.2% plastic strain. (d) Plastic strain induced by twin boundary migration versus the total plastic strain as a function of grain size.*

Novel DTEM Project

Professor Timothy P. Weihs	Dr. Thomas Voisin	Dr. Geoff Campbell
Johns Hopkins University	*Johns Hopkins University*	*Lawrence Livermore National Laboratory*

Scientists have long desired to image the evolution of microstructure when polycrystalline metals deform at high strain rates. Visualizing the motion of dislocations, twins, and cracks at high strain rates and at the nano-scale can shed light on the critical deformation mechanisms that are active. However, existing techniques simply lack the nanosecond time resolution and the nanometer spatial resolution that are needed to visualize these mechanisms *in situ*. To overcome these limitations and to explore the dynamic properties of metals under high-rate loading, we developed a novel straining stage capable of deforming thin foils inside a Transmission Electron Microscope (TEM) at strain rates ranging from quasi-static to $10^4 s^{-1}$. We image the rapid deformation by performing straining experiments inside the Dynamic TEM at the Lawrence Livermore National Laboratory in collaboration with Dr. Geoff Campbell and his group. This unique TEM offers the capability of taking nine 30ns exposures with delays between each image as short as 50ns and a space resolution lower than 20nm. This equates to imaging at 20 million frames per second over nine frames with a spatial resolution 100 times smaller than a typical bacterium. The short image times are created using high intensity electron pulses that are generated by bombarding a metal target with a laser. The electron pulses travel through a thin sample and are diffracted by defects within the sample, thereby providing an image of the microstructure. The transmitted electrons are distributed to one of nine different spots on a camera.

To deform small TEM specimens at high strain rates we designed and produced a novel sample holder. Two piezoelectric beams working in bending to load samples in tension and the samples have narrow gauge sections so as to achieve strain rates as high as $10^3 s^{-1}$. Strain gages mounted on each piezo record both displacement and force. The samples are prepared using a novel combination of femtosecond laser machining and precision ion milling to form 400µm wide metallic specimens with gauge sections that are 200µm wide, 50µm in length, and less than 100nm thick. During the *in situ* straining experiments a LabVIEW program is used to sync the motion of the straining stage with the nine electron pulses. This insures that the 9 images are captured before, during, and after the deformation occurs.

Initial experiments were performed using pure copper and pure magnesium samples. The nucleation of twins and their propagation across grains was observed, along with crack propagation and deformation associated with failure, all at strains near $4x10^3 s^{-1}$. Samples with the same geometry were also deformed *in situ* inside a conventional TEM at quasi-static strain rate and are being used to highlight the influence of the strain rate on the active deformation mechanisms. These initial observations and future observations will be used to support the overall MEDE effort that focuses on understanding and modeling the behavior of metals at high strain rates.

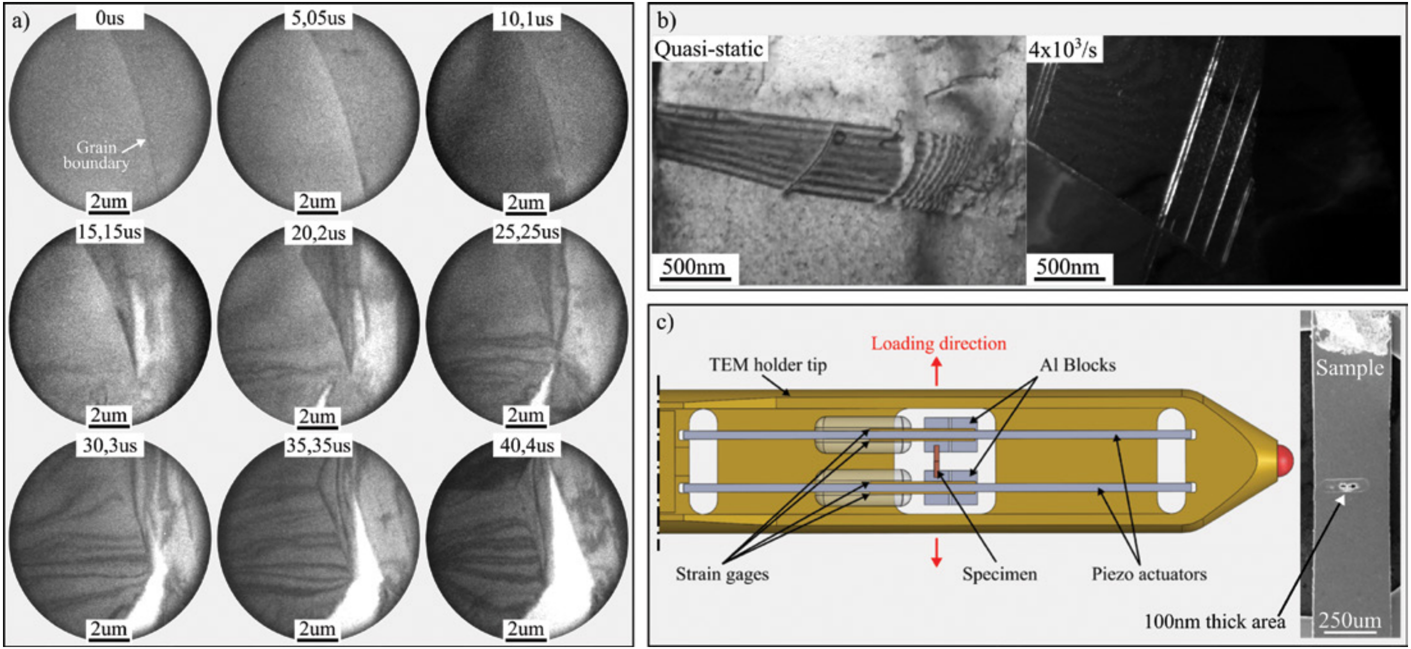


Figure 14: *In situ high-rate tensile testing in the Dynamic TEM. a) 9 TEM images captured while a pure magnesium sample was deforming at $4x10^3s^{-1}$. A crack can be seen to propagate across grains along specific crystallographic planes. b) Two TEM pictures highlighting both an increase in the twin number and a decrease in the thickness of twins in pure copper samples when strain rate rises from approximately $10^{-2}s^{-1}$ to $4x10^3s^{-1}$ c) 3D representation of the tip of the in situ DTEM straining stage where one can see the two piezoelectric actuators with strain gages attached. The specimen is mounted between the actuators and is loaded in tension when the actuators are triggered.*

DR. THOMAS VOISIN

Postdoctoral Researcher, Lawrence Livermore National Laboratory; Former postdoctoral fellow at Johns Hopkins University

MEDE Area of Research:
Defect nucleation, multiplication, and interactions at high strain rates

> "Collaborations and interactions between researchers are a big part of our core business. The MEDE program makes it possible at large scale — building bridges between many universities, national laboratories, and ARL. This has helped me not only to be visible to a larger community but also to learn new techniques, and, more importantly, new ways to manage my research, from many renowned experts."

DR. RICH BECKER

Fellow, U.S. Army Research Laboratory

MEDE Areas of Research:
Co-lead for Metals Group 3: Void Dominated Failure, also involved with Metals Groups Defects Properties Within a Grain and Plasticity Across Multiple Grains

"The span of integrated research in the MEDE program, from atoms to material response, provides an exceptional opportunity to develop a full array of methodologies and tools to tailor material performance."

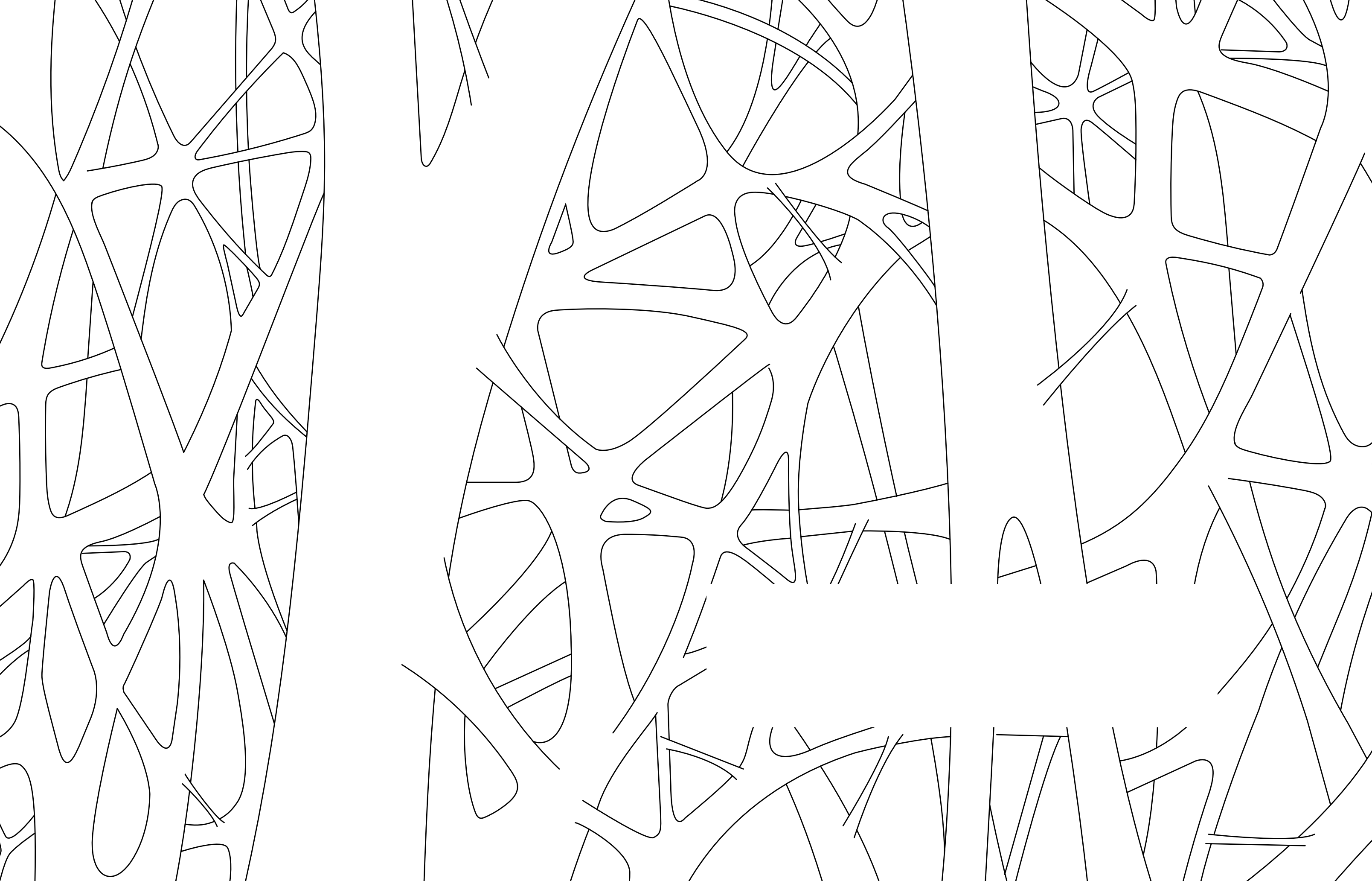
DR. TOMOKO SANO

Materials Engineer, U.S. Army Research Laboratory

MEDE Areas of Research:
Plasticity Across Multiple Grains, Void Dominated Failure, and Thermo-Mechanical Processing

"The goal of my research is to correlate critical aspects of the microstructure (e.g. defects, crystallographic orientation, grain boundary types), which are dependent on processing, to high strain rates properties, and major deformation and failure mechanisms. We will benefit the soldier by applying the knowledge of these correlations to design and develop the next generation of armor materials."

Artist rendering of polyethylene fiber as seen through an atomic force microscope.



POLYMERS

Consortium Lead - Prof. Giuseppe Palmese (Drexel)

ARL Lead - Dr. James Snyder

Polymers CMRG

CONSORTIUM PRINCIPAL INVESTIGATORS

Prof. Nicolas Alvarez, Drexel

Dr. Joseph Deitzel, Delaware

Prof. John W. Gillespie, Jr., Delaware

Prof. Vicky Nguyen, JHU

Prof. Giuseppe Palmese, Drexel

Prof. Mark Robbins, JHU

ARL COLLABORATORS

Dr. Jan Andzelm

Dr. Travis Bogetti

Dr. Kevin Masser

Dr. Kenneth Strawhecker

Dr. James Snyder

Dr. Tusit Weerasooriya

CONSORTIUM RESEARCH TASKS

- Characterization of Meso/Nanoscale Domains in UHMWPE Filaments (Deitzel and Gillespie, Delaware)
- Fabrication and Processing (Alvarez and Palmese, Drexel; Deitzel, Delaware)
- Micromechanical Model for the Strength and Failure Behavior (Nguyen, JHU)
- Modeling and Experiments of High Performance Polymer Fibers Subjected to Transverse Compression Loading (Gillespie, Delaware)
- Modeling Polymer Deformation: Potentials and Methods (Robbins, JHU)

Characterization of Meso/Nanoscale Domains in UHMWPE Filaments

Dr. Joseph M. Deitzel
University of Delaware

Professor John W. Gillespie, Jr.
University of Delaware

Dr. Ken Strawhecker
U.S. Army Research Laboratory

Dr. Travis Bogetti
U.S. Army Research Laboratory

Gel-spun high UHMWPE fibers are a critical component used in Army applications including both personnel and vehicle protective systems. Current state-of-the-art commercial materials exhibit mechanical properties that are much lower than theoretical predictions suggest is possible to achieve. The focus of the current work is to develop a more detailed understanding of how sub-filament meso/nanoscale structure determines the way load is translated through the filament cross section and along its length. Novel experimental techniques have been developed to indentify modes of failure that occur at different length scales and to quantify the energy associated with each mechanism.

High-resolution AFM imaging has enabled identification, mapping and quantification of the size distribution of fundamental structural units of the fibers. Novel meso and nanoscale features of sub-filament structure have been revealed in greater detail than ever before achievable. Examples include evidence that the base “microfibril” structure forms a 3-dimensional network[1], and that the surface of these “microfibrils” exhibit a nanoscale epitaxial, or “micro-shish kabob” texture[2]. Evaluation of gel-spun fibers with different processing histories has also shown significant changes in the mesoscale (100-1000 nm) structure, including the coalescence of small voids into large scale voids as the drawing process progresses[1].

The observation that fibrillation or the breaking up of these “microfibril” domains is a key mode of failure during transverse compression (or multi-axial loading) of these filaments [3] (Figure 15), has lead to a collaborative effort between UD-CCM and ARL to develop nanomechanical testing techniques to quantify the adhesive energy between adjacent microfibrils. The technique involves carrying out shallow (10-50nm) nanoindentation experiments using fine tipped AFM probes, with approximately 10nm radii, at the interface between 2 adjacent microfibrils. Upon reaching a critical load, the two fibrils split apart, forming a cat’s-eye, as seen in Figure 16. Using the energy associated with inelastic deformation obtained from the force-displacement curve, length of the cat’s-eye and diameter of the microfibrils, it is possible to calculate an effective adhesive fracture energy on the order of ~0.6J/m^2. It is important to note that this test probes properties on a very localized scale. Future efforts are focused on the use of nanoscratching techniques to investigate the role that other mechanisms, such as fracture of microfibril network junctions, may contribute to the work of adhesion over longer distances.

The work carried out in this program provides quantitative information regarding the relationship between processing conditions and meso/nanoscale structure in UHMWPE fibers. The insight gained from these efforts is shared with our MEDE collaborators at Drexel (Alvarez) in support of their processing studies. Furthermore, the information gained regarding sub-filament morphological structure and critical dimensions, as well as energies associated with modes of failure observed on the nanoscale are critical to developing accurate material models at all length scales. The experimental results and insights obtained through this effort are being shared with MEDE collaborators at ARL and JHU engaged in developing these computational tools. The experimental and computational tools developed through these collaborations enable a true “materials by design” approach to the development of the next generation of ballistic textiles used in personnel protection applications.

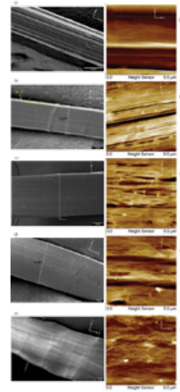


Figure 15: *SEM (left) and AFM (right) images of SK76 fiber surface features which have undergone transverse compression at different nominal strains: (a) As-given fibers at 0% (b) 22% (c) 31% (d) 51% (e) 71%. SEM and AFM images are not from the exact same fiber. Nominal strains are based on average fiber diameters. [3]*

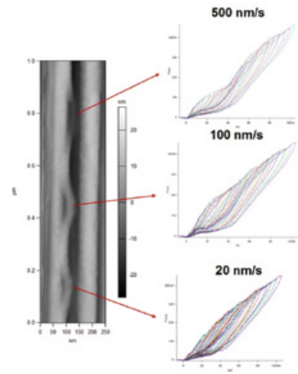


Figure 16: *AFM image (left) shows cat’s-eye deformation at 3 positions where nanoindentation resulted in the separation of two adjacent fibrils. Force-displacement curve series (right) indicate that the separation behavior of microfibrils may show some rate dependence.*

References:

1. McDaniel PB, Deitzel JM, Gillespie JW. Structural hierarchy and surface morphology of highly drawn ultra high molecular weight polyethylene fibers studied by atomic force microscopy and wide angle X-ray diffraction. Polymer 2015;69:148–58. doi:10.1016/j.polymer.2015.05.010.

2. Stockdale TA, Strawhecker KE, Sandoz-Rosado EJ, Wetzel ED. A rapid FIB-notch technique for characterizing the internal morphology of high-performance fibers. Mater Lett 2016;176:173–6. doi:10.1016/j.matlet.2016.04.082.

3. McDaniel PB, Sockalingam S, Deitzel JM, Gillespie JW, Jr., Keefe M, Bogetti TA, Weerasooriya T, Casem DT. The Effect of Fiber Meso/Nanostructure on the Transverse Compression Response of Ballistic Fibers. Submitted to Composites Part A.

MR. THOMAS C. O'CONNOR

PhD Candidate, Department of Physics and Astronomy, Johns Hopkins University

MEDE Area of Research:

Modeling Polymer Deformation: Potentials and Methods

> "MEDE has allowed me to explore and take risks at the interdisciplinary interface of physics and engineering. The training and support of the MEDE program have helped me develop research that is both impactful and applicable, and provided invaluable opportunities to practice collaborating and communicating my work with colleagues in engineering, government, and industry."

DR. JOSEPH M. DEITZEL

Senior Scientist, University of Delaware Center for Composite Materials

MEDE Area of Research:

Characterization of Meso/Nanoscale Domains in UHMWPE Filaments

"The work being performed in the Polymers CMRG is exciting because we are able to take advantage of advances in instrumentation and computing power to develop new experimental and computational tools that are being used to push beyond the current limits of our understanding of these materials. It is a great honor to be part of a historic effort that not only is leading to the development of the next generation of materials used to protect our soldiers, but also is substantially advancing our understanding of the physics of macromolecules."

DR. KEN STRAWHECKER

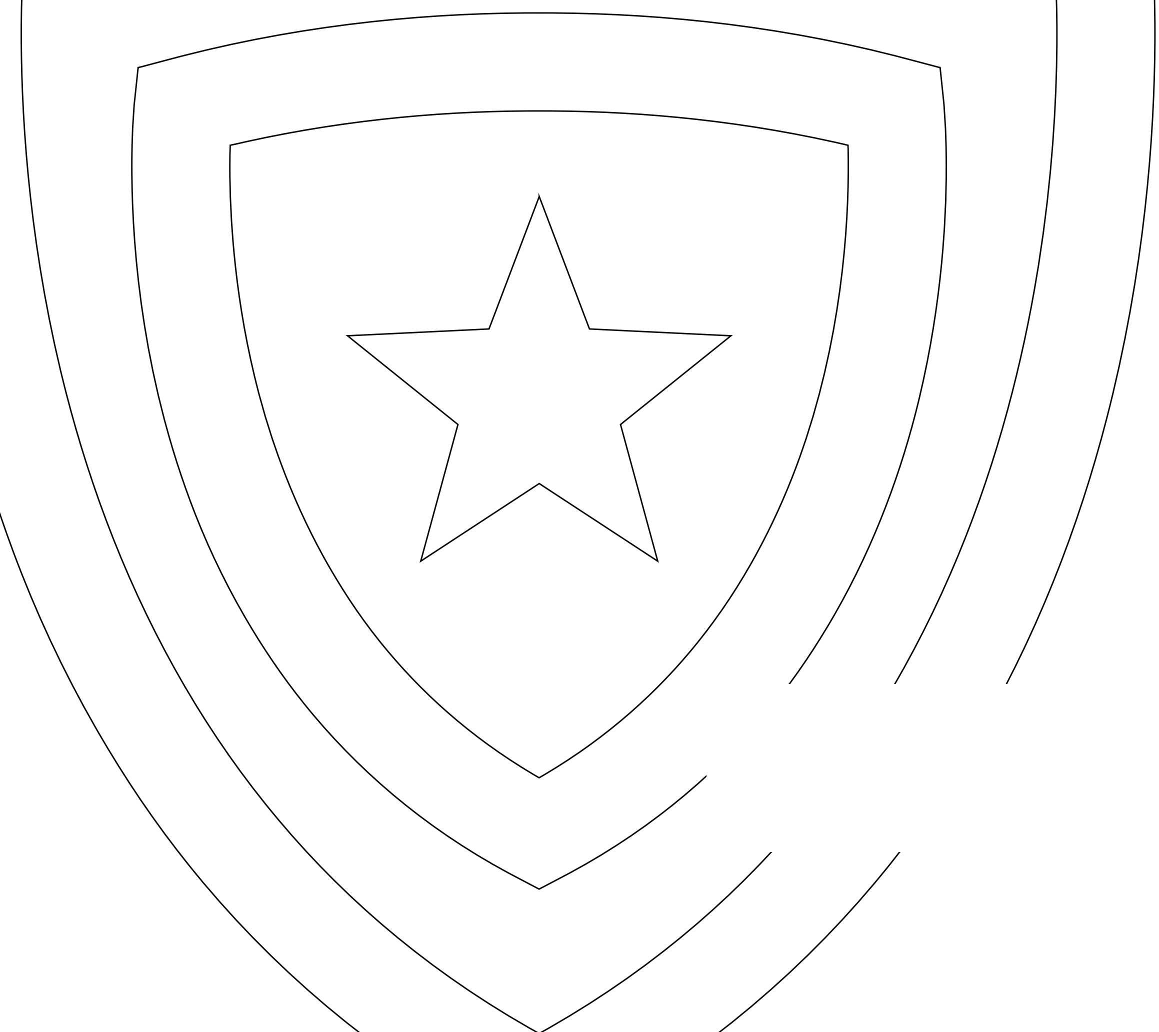
Materials Research Engineer, U.S. Army Research Laboratory

MEDE Area of Research:

Discovery of UHMWPE fiber morphologies and structure-property relationships at the fiber and sub-fiber length scale

"By applying nano-mechanical materials research techniques to ballistic fibers, we are working towards understanding the key mechanisms of strength and failure within these materials. This research will lead to engineering and design of the next-generation ballistic fiber which will be lighter-weight and have excellent strength."

The CMEDE shield symbolizes the protection and the strong collaboration found within the MEDE program.



INTEGRATIVE AND COLLABORATIVE TOOLS


Prof. K.T. Ramesh


Prof. Lori Graham-Brady


Prof. Michael Shields


Prof. Michael Kirby


Prof. Tamas Budavari


Dr. Betsy Rice


Prof. Tim Weihs


Dr. Richard Becker

SELECT CONSORTIUM PRINCIPAL INVESTIGATORS

Prof. Tamas Budavari, JHU

Prof. Lori Graham-Brady, JHU

Prof. Michael Kirby, University of Utah

Prof. K.T. Ramesh, JHU

Prof. Erica Schoenberger, JHU

Prof. Michael Shields, JHU

Prof. Timothy Weihs, JHU

SELECT ARL COLLABORATORS

Dr. Richard Becker

Dr. Travis Bogetti

Mr. Brian Leavy

Dr. William Mattson

Dr. Daniel J. O'Brien

Dr. Betsy Rice

Mr. Wayne Ziegler

INTEGRATIVE RESEARCH ACTIVITIES

- Probabilistic Modeling & UQ for Computational Models of Composites (Graham-Brady and Shields, JHU)
- Data Science: Integration (Budavari, JHU)
- Novel DTEM Project (Weihs, JHU)
- Benchmarking Effort (Ramesh, JHU)
- Collaboration Study (Schoenberger, JHU)

Probabilistic Modeling and Uncertainty Quantification for Computational Models of Composites

Professor Lori Graham-Brady	Professor Michael Shields	Professor Michael Kirby
Johns Hopkins University	*Johns Hopkins University*	*University of Utah*

Goal: The long-term goal of this project is to develop a framework for uncertainty quantification (UQ) and/or probabilistic modeling of materials for armor applications. The current applications of this framework include mesoscale models of composites and ceramics with random microstructure, and molecular dynamics studies of polymers.

Research strategy: Assembling a joint team from the MEDE and MSME CRAs and ARL that addresses probabilistic modeling and UQ for mechanics, the approaches to efficient sampling of high-dimensional parameter space developed in this task have enabled studies of composites, ceramics, and molecular-scale behavior of materials.

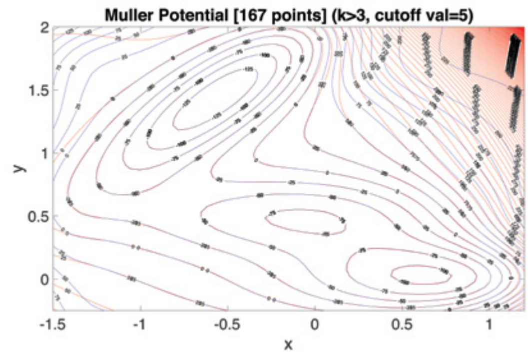


Figure 17: *Reconstruction of a Muller potential with a minimal number of MD simulations, using adaptive sparse grid sampling.*

Figure 18: *Stress contours corresponding to a unit cell model of a single fiber in a matrix, with debonding at the interface.*

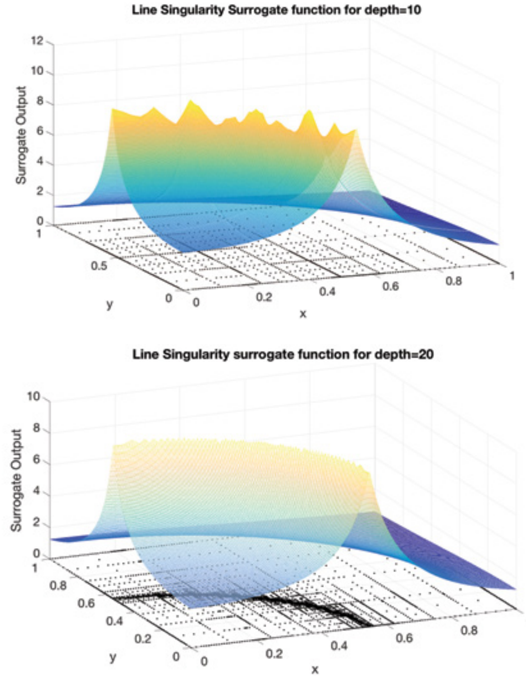


Figure 19: *Adaptive sparse grid sampling in two-dimensional space, capturing a discontinuous response surface with minimal number of model evaluations. This is expected to be particularly important for composite behavior such as debonding which will lead to such discontinuities.*

Data Science: Integration

Professor Tamas Budavari
Johns Hopkins University

Mr. Wayne Ziegler
U.S. Army Research Laboratory

This year has seen a focus in publishing work on our data collaboration platform, working with and learning from the wider materials data research community, and preparing for a MEDE SciServer installation and deployment. Over the past year, we have published a paper in the Integrating Materials and Manufacturing Innovation Journal detailing our experiences in adapting SciServer into a materials research data collaboration platform. Following our presentations of the paper, we've met and collaborated with Wayne Ziegler and learned from his experiences managing the technical aspects of materials research at the ARL. Furthermore, we've presented to and regularly participated in a Materials Research Data Sub Committee organized by Ms. Afina Lupulescu of ASM International; Afina formed the committee to bring together materials data scientists from across the industry to share techniques regarding data platforms applied to materials research and discuss ideas and developments in establishing standardized materials data formats. Finally, having completed a successful prototype, our team focused on overcoming deployment issues. Working with the SciServer developers, we've practiced the deployment processes and evaluated several installation scenarios appropriate for MEDE's requirements; our current design and implementation integrates the recently purchased MEDE server hardware with the existing SciServer hardware infrastructure in order to leverage the platform's parallelism while we evaluate the security requirements of the MEDE project.

Figure 20: *Following the SciServer production release during the Summer of 2016, the online, browser-based tools driving collaborative materials research are now publicly available at www.sciserver.org.*

ADDITIONAL COLLABORATIVE ACTIVITIES

ARL Open Campus

The MEDE CRA embraces the ARL Open Campus Initiative. The highly collaborative nature of the MEDE program intrinsically supports consortium members working side by side with ARL scientists and engineers. In addition to taking advantage of ARL's laboratories at Aberdeen Proving Ground in Maryland, CRA members frequently utilize facilities at other MEDE consortium locations. Johns Hopkins University, Rutgers University, and the University of Delaware each have dedicated space for ARL researchers. This promotes the building of a science and technology ecosystem that encourages groundbreaking advances in basic and applied research areas of relevance to the Army.

UK Collaboration with the MEDE Programme

Contributed by: Professor Paul Curtis FREng

The UK Ministry of Defence at Dstl funds a major materials research activity centred around the Materials and Structures (MAST) programme. Although this covers all aspects of materials behaviour, this has significant elements on the behaviour of materials at high loading rates in ballistic and blast scenarios. The UK has a government collaboration agreement signed with ARL which permits collaboration on materials and has been collaborating with the US for many years. With the advent of the MEDE programme, the US and the UK identified an opportunity for further collaboration in this important area of materials technology.

Dstl staff have attended nearly all of the MACH meetings held each year in Annapolis, as well as the last two internal meetings in the fall each year. This has allowed Dstl and the MEDE management to identify a number of areas where UK-US collaboration would be potentially fruitful.

Collaboration is now underway on elements of the ceramics and polymers activities in the MEDE programme, with UK-US meetings having been held, information exchanged and some joint research starting to be performed. This has included some joint work on modelling high rate events and evaluating materials provided by the US. Both Dstl and ARL are hopeful of further and more extensive collaboration between UK and US researchers in the future.

MEDE Fall Meeting

The MEDE Fall Meeting is an annual, closed event that brings the entire MEDE CRA together for two days of collaborative activities and discussion. In 2016, the event was attended by 131 individuals including special guests from the United Kingdom's Defence Science and Technology Laboratory, Army Research Office, U.S. Army Corps of Engineers, and the Office of Naval Research. Professor K.T. Ramesh (Johns Hopkins University) and Dr. John Beatty (ARL) led the meeting, which focused on technical collaboration across the MEDE CRA and program planning for the upcoming year.

Mach Conference

The Mach Conference is an annual, open event that showcases the state of the art of multiscale research in materials, with an emphasis on advancing the fundamental science and engineering of materials and structures in extreme environments. MEDE CRA members are significant participants in this event, which shares research discoveries to the broader community.

SIGNIFICANT MEETINGS AND VISITS

Research Management Board

On January 6, 2016, the Research Management Board (RMB) convened at Johns Hopkins University to review the Enterprise for Multiscale Research of Materials. Hosted by the Army Research Laboratory and the Office of the Assistant Secretary of the Army for Acquisition, Logistics and Technology, this review led to the renewal of the MEDE program for the second five years.

MEDE Science Advisory Board

The MEDE Science Advisory Board is convened annually to review the scientific and collaborative activities within the program. The Board's recommendations in coordination with those from ARL's Technical Advisory Board are used to help prioritize research activities and shape the overall program.

Congressman C.A. Dutch Ruppersberger

Legislative staffers from the Office of U.S. Representative C.A. Ruppersberger (Maryland, Second District) visited CMEDE facilities at Johns Hopkins University on April 12, 2016.

Honorable Stephen P. Welby

CMEDE also had the pleasure of welcoming the Honorable Stephen P. Welby, Assistant Secretary of Defense for Research and Engineering, to Johns Hopkins University on September 12, 2016. Mr. Welby met with University and CMEDE leadership and toured CMEDE research activities.

Photo: Will Kirk, Homewood Photography

1. *Dr. John Beatty presents to the Research Management Board*

2. *Legislative staffers from the Office of U.S. Congressman C.A. Dutch Ruppersberger visit CMEDE facilities*

3. *The Honorable Stephen P. Welby sees examples of work being completed at JHU*

RELATED ACADEMIC PROGRAMS

In addition to its research activities, CMEDE runs several academic programs that broaden the scientific impact of the MEDE program.

Traditional

- Short Courses – Two day courses co-sponsored by the Hopkins Extreme Materials Institute that are taught by recognized experts in the area of materials in extreme dynamic environments. Attendees include representatives from academia, government and industry.
- Lectures and Seminars – CMEDE supports the Enterprise for Multiscale Research of Materials lecture series that helps to educate and promote collaboration across the entire enterprise.
- MEDE Undergraduate Internships – Paid summer internships for students at the MEDE Consortium locations that assist in developing research skills for undergraduate students.

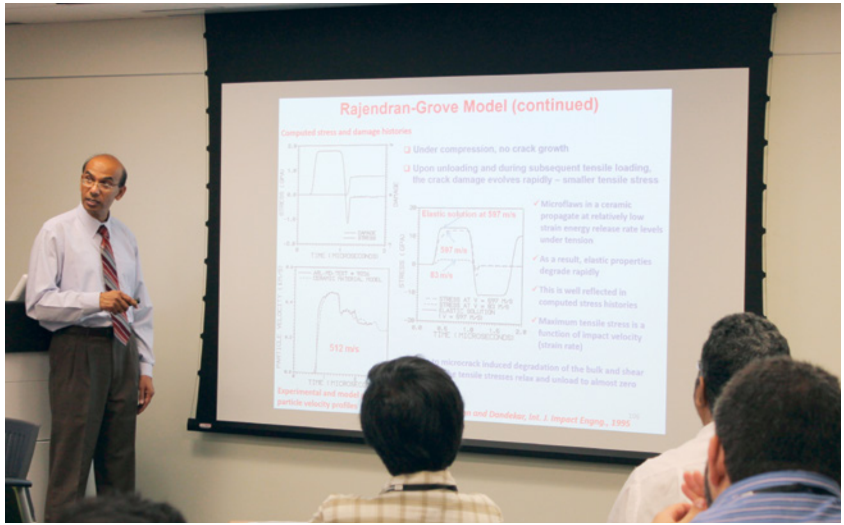


Figure 21: *Prof. Ghatu Subhash, University of Florida*

Collaborative

- Army Educational Outreach Program – The Army Educational Outreach Program (AEOP) provides opportunities for K – undergraduate students to participate in STEM apprenticeships, internships and competitions. For 2016 – 2017, the Hopkins Extreme Materials Institute (HEMI), parent to CMEDE at Johns Hopkins University was selected as a host site for AEOP's Research and Engineering Apprenticeship Program (REAP). In the summer of 2016, four high school students were selected as REAP apprentices and participated in research activities under the supervision of CMEDE principal investigators and mentors.

  Additionally, with significant involvement with Army sponsored research through CMEDE, HEMI was awarded an AEOP Strategic Outreach Initiatives grant. The grant will help promote AEOP opportunities and STEM programs sponsored by Johns Hopkins Center for Educational Outreach with a particular focus towards Baltimore City schools, and military families stationed at Aberdeen Proving Ground and Adelphi Laboratory Center locations. CMEDE's involvement with AEOP demonstrates a commitment to supporting the US Army's strategic goals for promoting STEM activities and the next generation work force.

- Extreme Science Internships (ESI) – The ESI program is a year-round, paid internship program with Morgan State University. ESI provides internal internships at Morgan State to allow students to develop their research skills before participating in an external internship at a MEDE CRA location. ESI has been a highly successful program and serves as a model collaboration for student development.

- HEMI/MICA Extreme Arts Program – The HEMI/MICA Extreme Arts Program is a new initiative that brings faculty and students from Johns Hopkins University and the Maryland Institute College of Art (MICA) together to explore unique perspectives on extreme events. The program aims to encourage collaboration among artists and researchers to examine data, interpret outcomes, and translate results from extreme events in new ways. It is our hope that this dialogue will create a stronger community through a shared sense of curiosity and exploration. CMEDE is a significant participant in this program.

1

2


Polymer Challenges
Polymers encompass a wide range of properties
Rubbers, in particular, require sensitive force measurements, but als
Low stiffness leads to low sound speed and hence natural frequency
Lateral inertia can cause ringing effects
Properties of silk fibres, Holland and Vollrath OSG 2005

1. *CMEDE Seminar: Dr. Stefan Hiermaier, Ernst Mach Institut*
2. *CMEDE Seminar: Dr. Clive Siviour, University of Oxford*
3. *2016 AEOP Research in Engineering Apprenticeship students*
4. *2016 Morgan State University ESI interns*
5. *Image from Prof. Jay Gould, HEMI/ MICA Extreme Arts Program 2016 Artist-in-Residence*

CMEDE STRATEGIC PARTNERSHIPS

MEDE has established strategic partnerships with several key organizations. These partnerships enable CMEDE to collaborate, leverage resources and broaden its impact to the scientific community.

Subcommittee of the Materials Genome Initiative (SMGI) of the National Science and Technology Council	**Center for Composites Materials (CCM)**	**Army Educational Outreach Program**
US Advanced Ceramics Association (USACA)	**Center of Excellence on Intergrated Materials Modeling**	**Maryland Advanced Research Computing Center (MARCC)**

Lightweight Innovations for Tomorrow (LIFT)	**Ceramics, Composite and Optical Materials Center (CCOMC)**	**U.S. Naval Research Laboratory**	**National Institutes of Standards and Technology**

EXPANSION ANNOUNCEMENT: ADDITION OF NC A&T AND UNCC TO MEDE CRA

This year, we are pleased to welcome North Carolina Agricultural and Technical State University (NC A&T) and the University of North Carolina at Charlotte (UNCC) to MEDE CRA. Their addition was made possible through the competitively awarded Partnered Research Initiative (PRI) sponsored by the Army Research Office. The PRI provides Historically Black Colleges and Universities/Minority Institutions an opportunity to participate in one of the six highly collaborative ARL research programs.

The NC A&T/UNCC research task titled, "Tailoring Mg-alloy Systems through Composition/Microstructure/Severe Plastic Deformation for Army Extreme Dynamic Environment Application" will be integrated into the Metals CMRG with a focus on enhancing the processing activities.

Prof. Jagannathan Sankar, NC A&T

Prof. Qiuming Wei, UNCC

Dr. Zhigang Xu, NC A&T

Dr. Sergey Yarmolenko, NC A&T

CMEDE LEADERSHIP AND STAFF MEMBERS AT JOHNS HOPKINS UNIVERSITY

CMEDE Leadership

Prof. K.T. Ramesh
Director

Prof Lori Graham-Brady
Associate Director

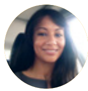
Dr. Victor Nakano
Executive Program Director

CMEDE Staff

Jessica Ader
Modern Media Coordinator

Bess Bieluczyk
Senior Administrative Coordinator

Andre Bothelo
Software Engineer



Angela Coleman
Budget Analyst

Scott McGhee
Senior Administrative Manager

Melissa Rosenberger
Budget Analyst

Phyllis Sevik
Research Service Manager

Matthew Shaeffer
Staff Engineer

Adam Sierakowski
Software Engineer

Katie Vaught
Administrative Assistant

Mehwish Zuberi
Junior Database Administrator

ABBREVIATIONS AND ACRONYMS

ARL	Army Research Laboratory
AEOP	Army Educational Outreach Program
CALTECH	California Institute of Technology
CCM	Center for Composite Materials
CCOMC	Ceramic, Composite and Optical Materials Center
CEIMM	Center of Excellence on Integrated Materials Modeling
CMC	Consortium Management Committee
CMEDE	Center for Materials in Extreme Dynamic Environments
CMRG	Collaborative Materials Research Group
CTRG	Collaborative Technical Research Group
CRA	Collaborative Research Alliance
DELAWARE	University of Delaware
DOD	Department of Defense
DREXEL	Drexel University
DSTL	Defence Science and Technology Laboratory
DTEM	Dynamic Transmission Electron Microscope
EMRM	Enterprise for Multiscale Research of Materials
ESI	Extreme Science Internship
HEMI	Hopkins Extreme Materials Institute
JHU	Johns Hopkins University
MEDE	Materials in Extreme Dynamic Environments
MEDE CRA	MEDE Collaborative Research Alliance
MGI	Materials Genome Intitative
MICA	Maryland Institute College of Art
MSU	Morgan State University
NC A&T	North Carolina Agricultural & Technical State University
NIST	National Institute of Standards and Technology
NMT	New Mexico Institute of Mining and Technology
PRI	Partnered Research Institution
PURDUE	Purdue University
REAP	Research in Engineering Apprenticeship Program
RMB	Research Management Board
RUTGERS	Rutgers University
STEM	Science, Technology, Engineering and Math
UHMWPE	Ultra High Molecular Weight Polyethylene
UNCC	University of North Carolina at Charlotte
UTSA	The University of Texas at San Antonio
WSU	Washington State University

PROF. ROBERT C. CAMMARATA II

Professor of Materials Science and Engineering, Johns Hopkins University

> Bob was a kind, caring, and supportive friend and mentor to so many. His warmth, selflessness, and concern for others are the qualities that made him such an effective teacher and admired person. His passion for his research and the caring he demonstrated toward his students and his colleagues set an example for everyone who knew Bob, and are the legacy he has given to the Whiting School and to Johns Hopkins University.

IN MEMORIAM: PROF. ROBERT C. CAMMARATA II

Robert "Bob" Cammarata, professor of materials science and engineering and a member of the Hopkins Extreme Materials Institute, an insightful scientist, a talented teacher, a visionary entrepreneur, a mentor to students and colleagues, and a leader in the Johns Hopkins community, died on January 13, 2016.

Bob joined the Whiting School of Engineering (WSE) faculty in 1987 after completing a doctorate in applied physics at Harvard and a postdoctoral fellowship at MIT. At WSE, Bob quickly established a reputation as a visionary researcher and a talented educator, and took on leadership roles both within WSE and in the university at large - serving as a member of the Homewood Academic Council and shaping the Department of Materials Science and Engineering's current focus and curriculum. Bob also was a skilled educator and, in 2010, he was recognized with the McDonald Award for Excellence in Mentoring and Advising for his ability to engage minds, elevate spirits, and encourage his students' best efforts.

Bob oversaw a vibrant research program at WSE, where he was an integral member of the former Materials Research Science and Engineering Center and, more recently, was a key researcher in HEMI. Over the years, he received significant recognition for his studies on the fundamental thermodynamics and mechanics of thin films. He was elected as a Fellow of the Materials Research Society in 2011 and the American Physical Society in 2012. In recent years, his research focus shifted to carbon nanotubes and developing cost effective and more efficient ways of separating semiconducting nanotubes from metallic nanotubes. Bob and his former student, Stephen Farias, PhD '14, founded NanoDirect to commercialize a technology he developed to separate different types of nanowires and nanoparticles.

Within the CMEDE program, Bob was a constant support – participating in the Metals CMRG and serving as an advisor for students within our MEDE Undergraduate and Extreme Science Internship programs.

Most importantly, Bob was a kind, caring, and supportive friend and mentor to so many. His warmth, selflessness, and concern for others are the qualities that made him such an effective teacher and admired person. His passion for his research and the caring he demonstrated toward his students and his colleagues set an example for everyone who knew Bob and are the legacy he has given to the Whiting School and to Johns Hopkins University.

Bob is survived by his wife, Sharka Prokes, his brother, Ronald Cammarata, and his sister-in-law, Norma Cammarata.

HEMI.JHU.EDU/CMEDE

For more information on CMEDE, visit us at: hemi.jhu.edu/cmede,
call us at 410-516-7257 or email us at mede@jhu.edu.

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