U.S. ARMY COMBAT CAPABILITIES DEVELOPMENT COMMAND – ARMY RESEARCH LABORATORY

ADVANCED MANUFACTURING FOR THE PURSUIT OF HETEROGENOUS CERAMIC DESIGN

[1]Lionel Vargas-Gonzalez, Ph.D., [1]Nicholas Ku, Ph.D., [1]Andrew Rosenberger, Ph.D., and [2]Joshua Pelz

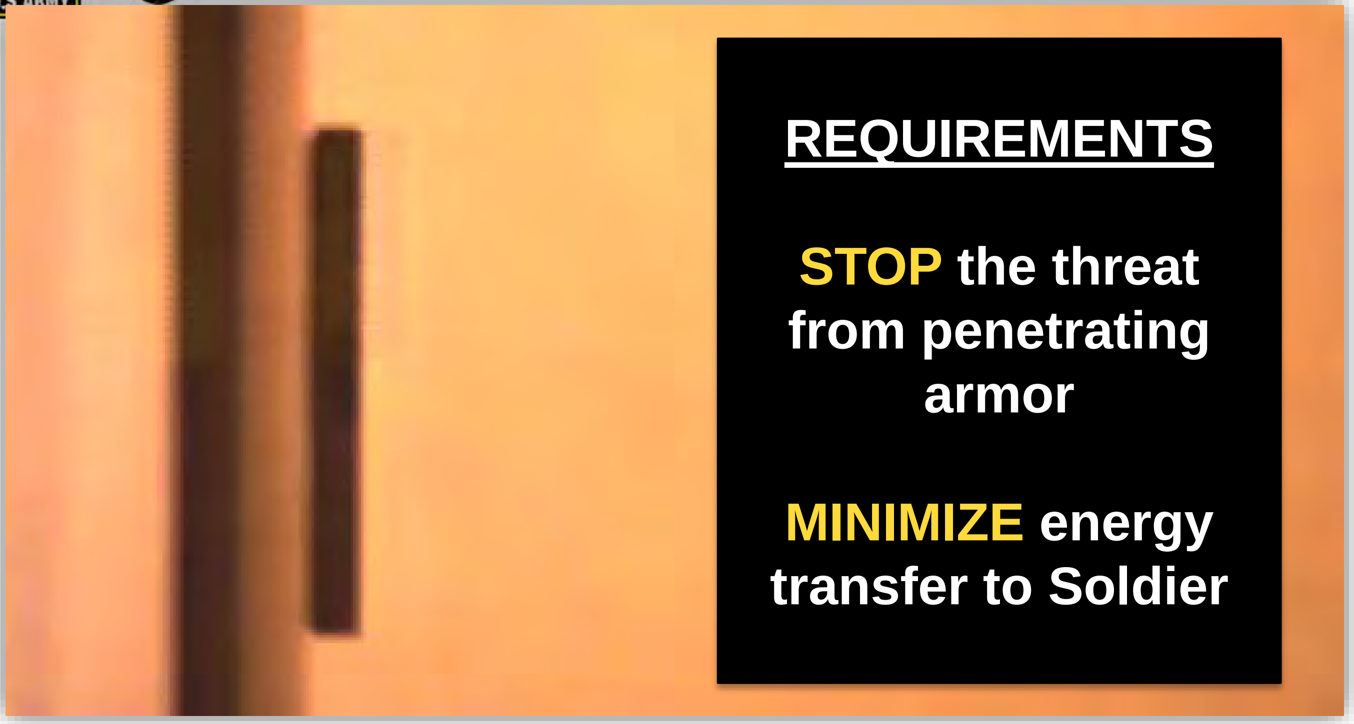
[1]DEVCOM Army Research Laboratory, [2]University of San Diego

13 APR 22

WHY WE FIGHT: PROTECT OUR GREATEST ASSET

Images courtesy of U.S. Army and Marine Corps Public Affairs
https://www.dvidshub.net/image/30300/hard-headed-marine-walks-away-shot-helmet
https://www.dvidshub.net/image/21019/sapis
https://www.army.mil/article/3908/soldier_uses_his_head_in_fight

SOLDIER PROTECTION



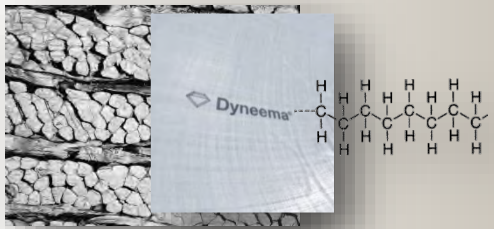
REQUIREMENTS

STOP the threat from penetrating armor

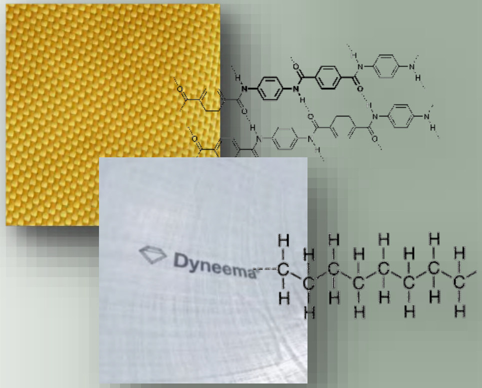
MINIMIZE energy transfer to Soldier

Material	Density (g/cm^3)	Weight of 10”x12”x0.3” Plate (lb)
Boron Carbide	2.52	3.9
Silicon Carbide	3.21	5.0
UHMWPE	0.98	1.3
Steel	7.8	12.3

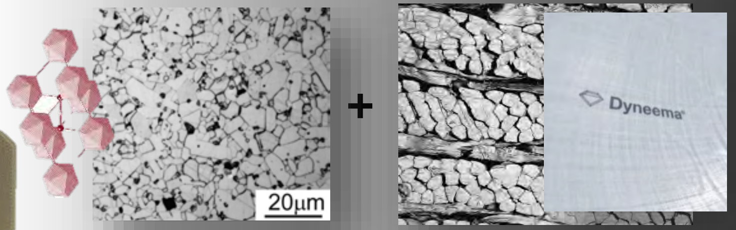
Ultra-High Molecular Weight Polyethylene (UHMWPE)



UHMWPE or Aramid Fiber



Ceramic (B_4C, SiC) + UHMWPE Backer

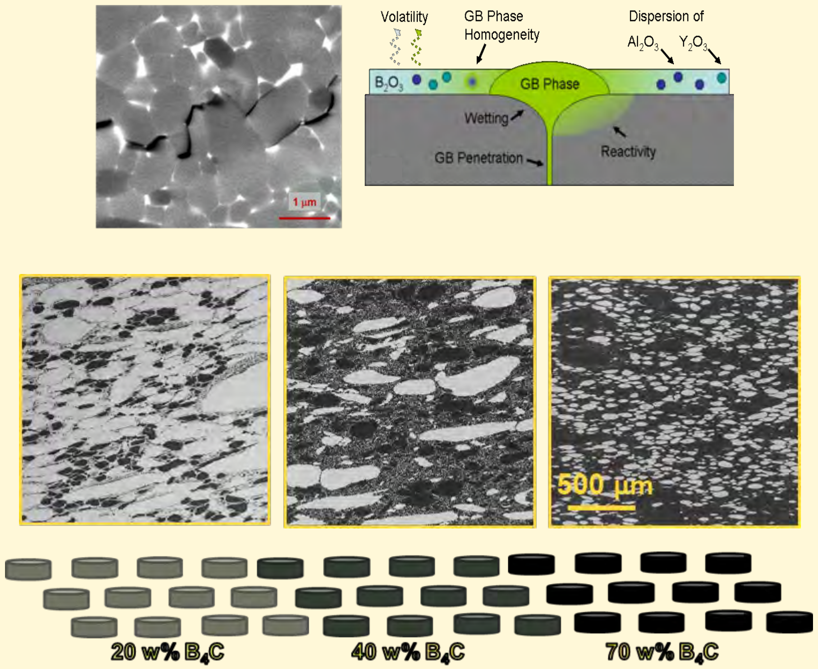


IT’S A BALANCING ACT BETWEEN PROTECTION AND BURDEN

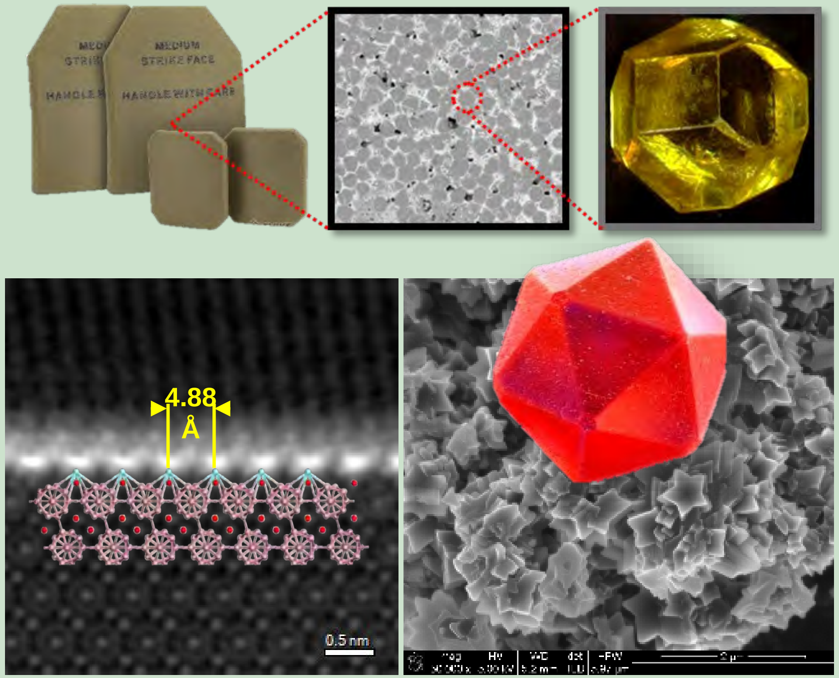
NOVEL MATERIALS AND ADVANCED MECHANISMS ARE KEY

There are multiple approaches to enhancing ceramic armor performance:

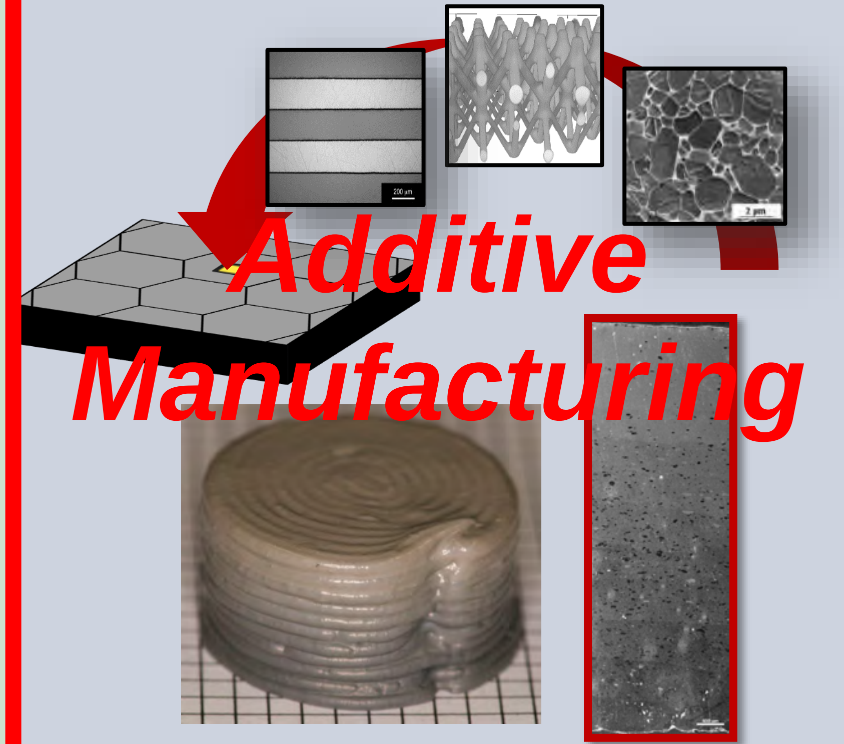
Improve current state-of-the-art materials by refining microstructures/properties



Develop or enable novel, superhard, and lightweight materials



Invoke new or advanced defeat mechanisms in armor through design

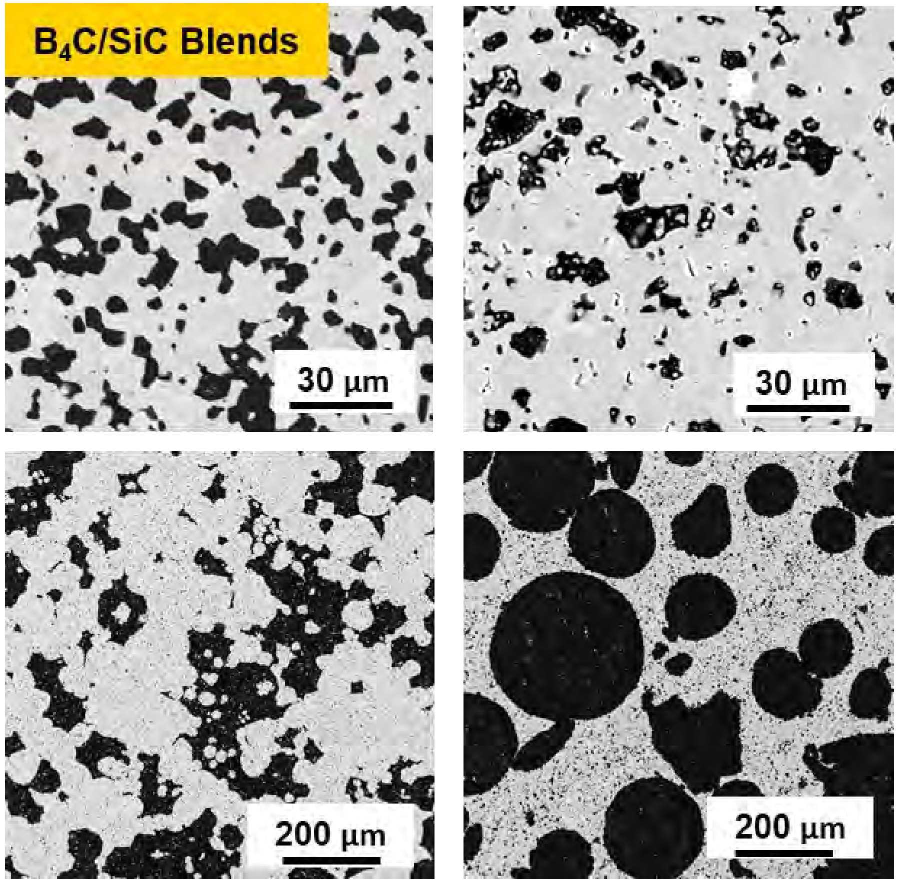


VISION: CERAMIC DESIGN TO ENABLE *NOVEL ARMOR MECHANISMS*

DEVCOM ARMY RESEARCH LABORATORY

Push beyond conventional powder processing methods to open armor design space

B_4C/SiC Blends

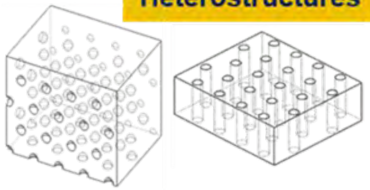


Examples of possible B_4C and SiC composite microstructures

Design limited to stochastic powder mixing!

Mesoscale designs enabled through advanced processing

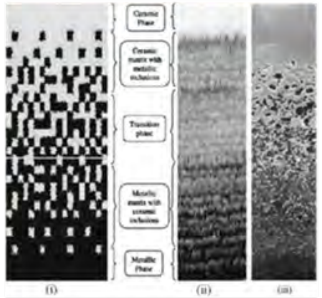
Heterostructures



Periodic Structures; Dunn (ARL)

HRL SiOC Lattices through Precursor SLA

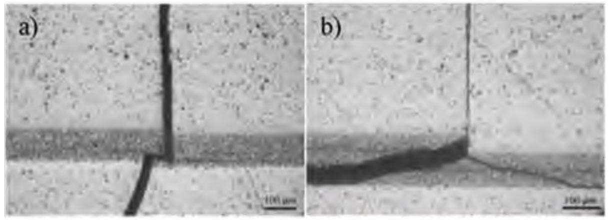
Functional Grading



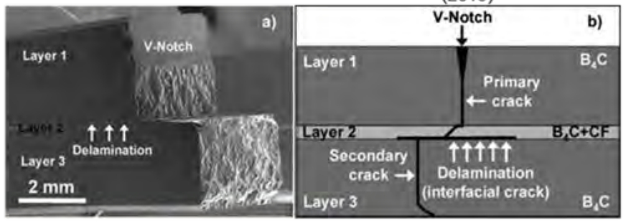
Metal Ceramic FGMs
A. Gupta, PAS. 79, 1–14 (2015)

Interface and Texture Engineering

Equiaxed and Textured Al_2O_3 Layers Pavlacka et al., JACS (2013)

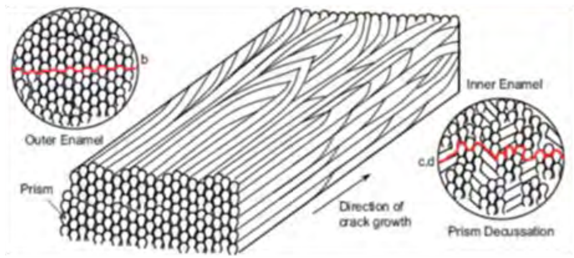


Transformation toughening for Al_2O_3/ZrO_2; Tarlazzi et al., Wear 244 (2000)

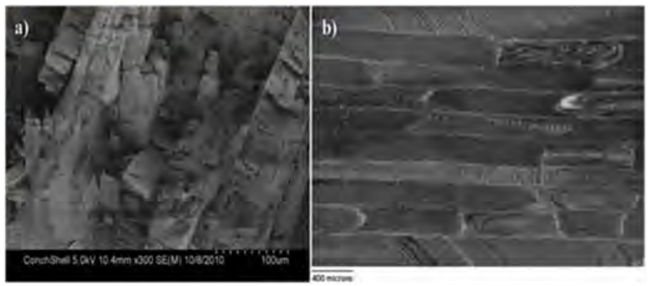


Boron Carbide with weak interlayer; M. Lugovy, Ceram Int 37 (2011)

Bio-inspiration and Hierarchical Structures



Decussation in Human Teeth Enamel;
D. Bajaj, D.D. Arola / Biomaterials 30 (2009) 4037–4046

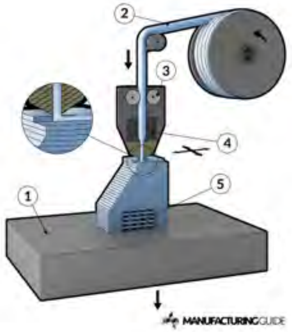


SHELL Technique for Strombug Gigus Structures;
Karambelas et al., Ceram. Int. 39 (2013)

CERAMIC AM METHODS AT DEVCOM ARL

DEVCOM ARMY RESEARCH LABORATORY

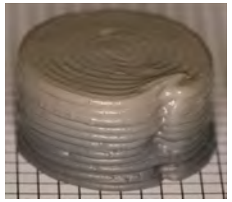
Material Extrusion (Direct-Ink-Write)



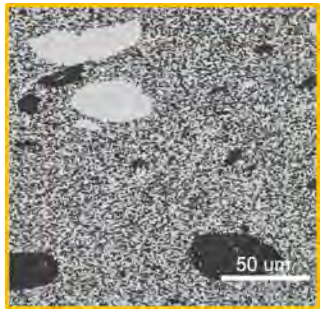
- Ability for multi-material printing for functional gradient parts

ARL Modified LulzBot Taz6

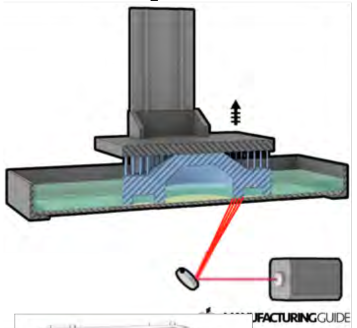
ARL-TR-8851 (2019)



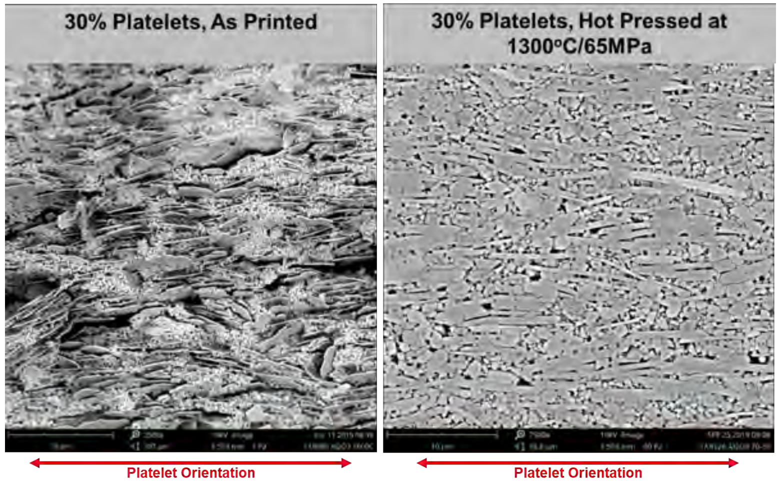
Graded SiC-B4C part with microstructure shown right



Vat Polymerization (Stereolithography)



- Finest resolution
- Ability to create complex shapes



Powder Bed Fusion (Binder Jetting)

- Scalable for industrial applications
- Ability to create complex shapes

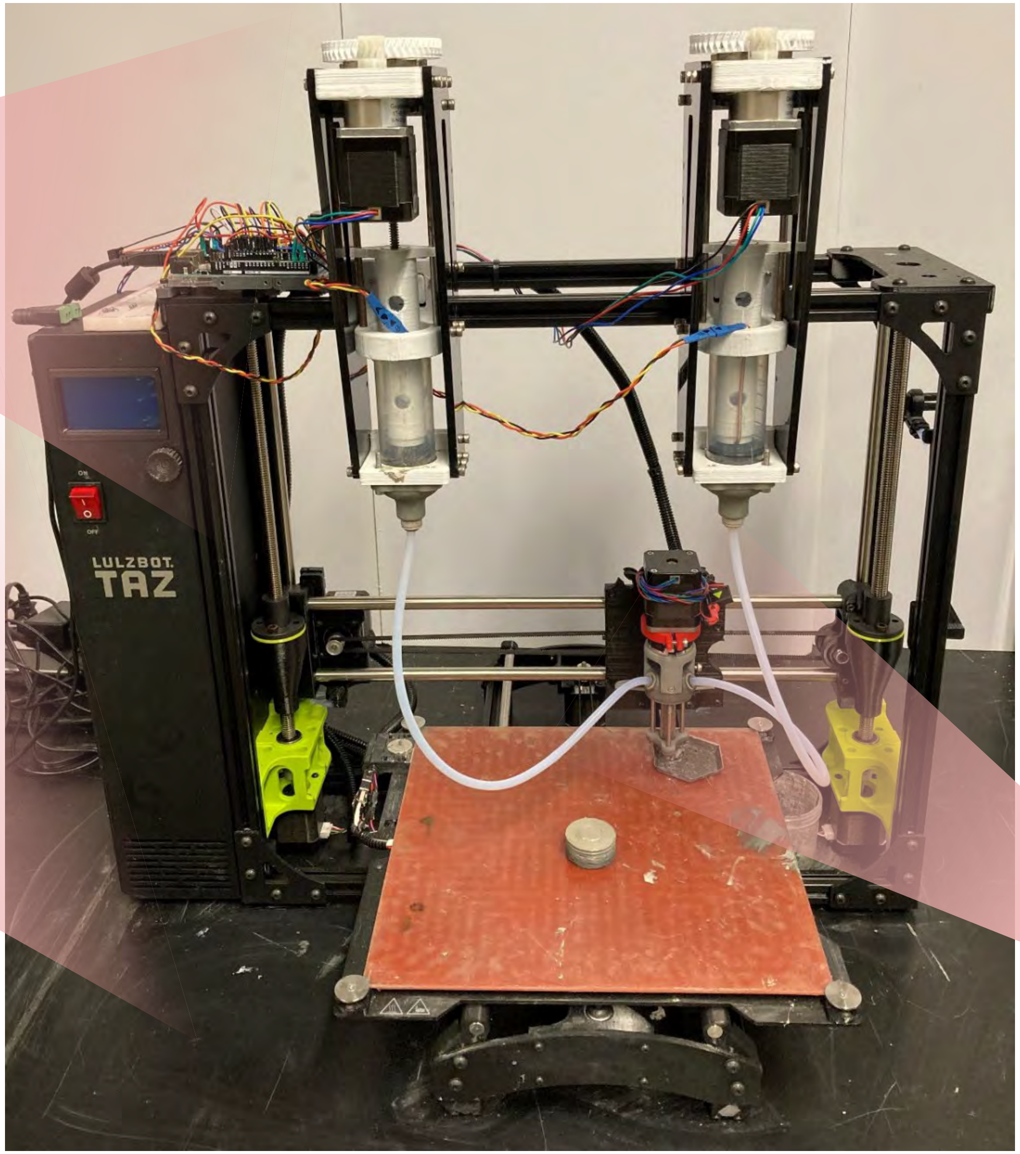
AFC logo made of SiC armor ceramic on the ExOne Innovent+

ARL DIRECT-INK-WRITE (DIW) SYSTEM

DEVCOM ARMY RESEARCH LABORATORY

Feed System

Precise, Plunger-Driven
Volumetric Feed
Scalable FS Units

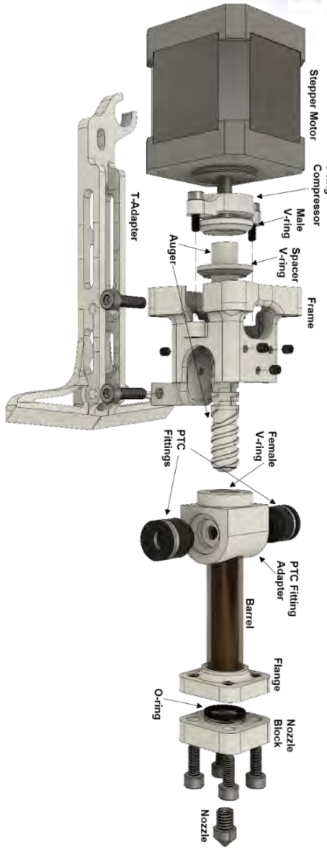


Base System

LulzBot Taz 6
Aleph Objects, Loveland, CO

Components 3D printed using the provided FDM toolhead

ARL-TR-8851 (2019)



Print Head

Multimaterial
In-Line Mixing
Interchangeable Nozzle

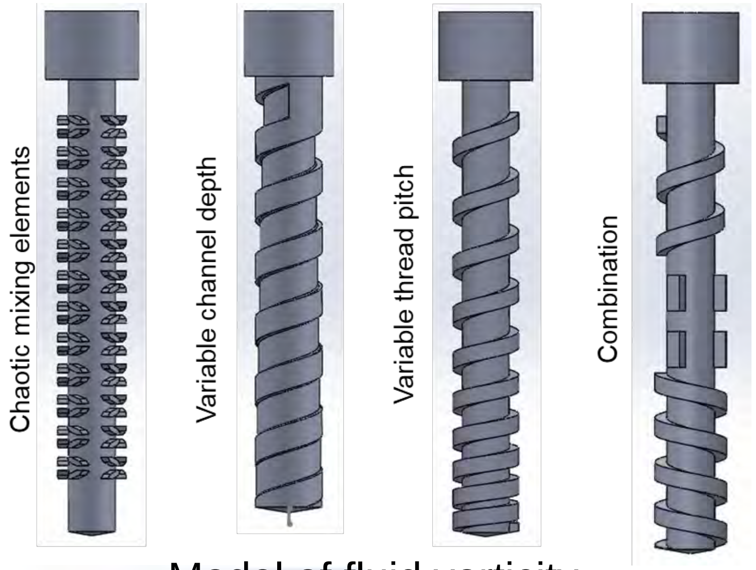
Custom system for co-printing of multiple materials with in situ composition control

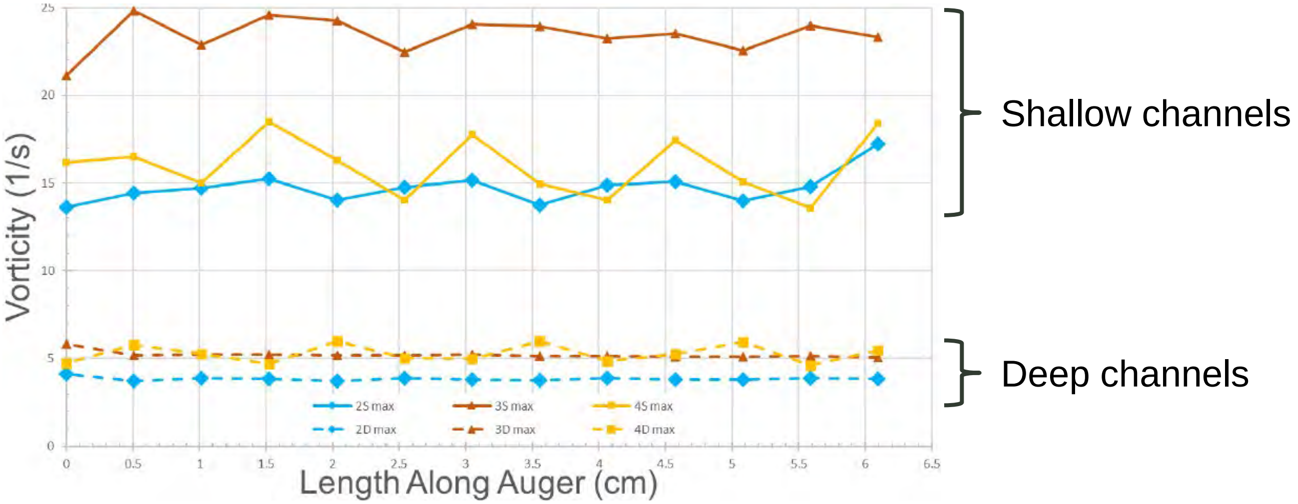
EXTERNAL LEVERAGING WITH USMA – AUGER DESIGN

USMA CAPSTONE PROJECT – TEAM "THE FINE PRINT"

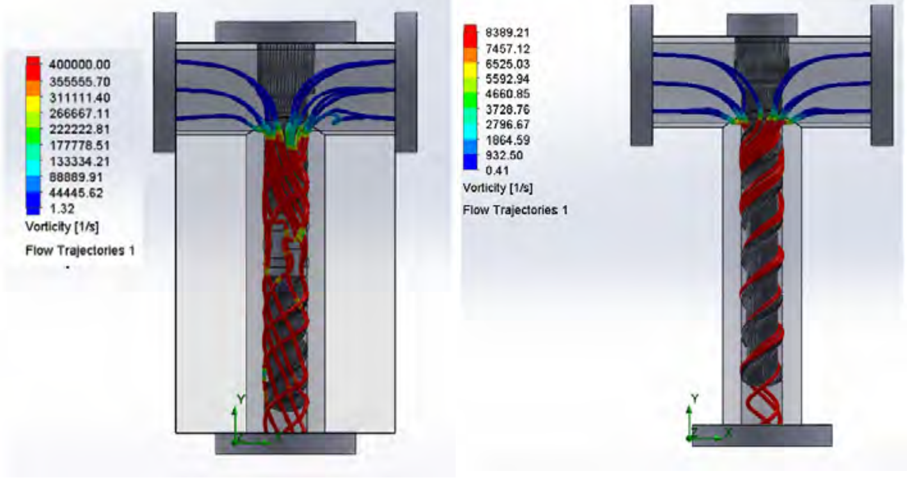
CDTs Campanella, Figueroa-Cecco, Fujinaka, and Sasek
Mentor: LTC Nowicki

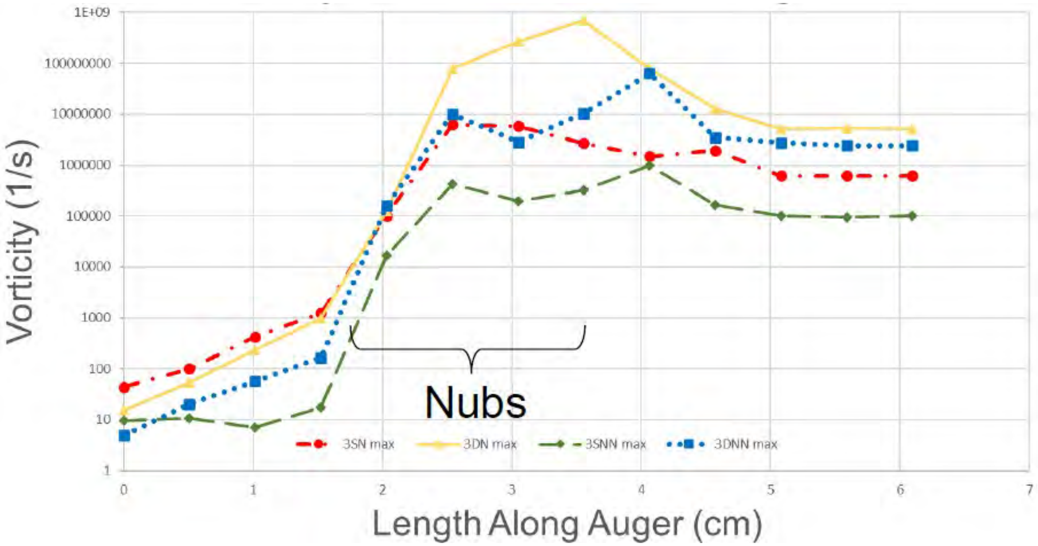
Auger designs with different mixing features





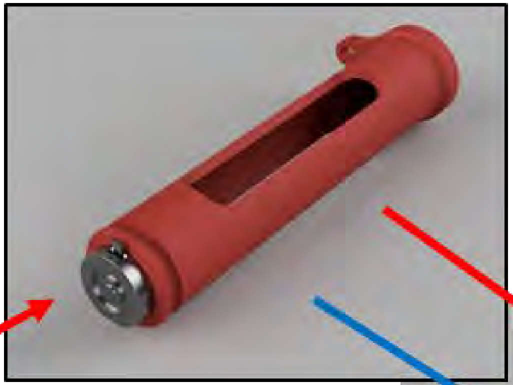
Model of fluid vorticity





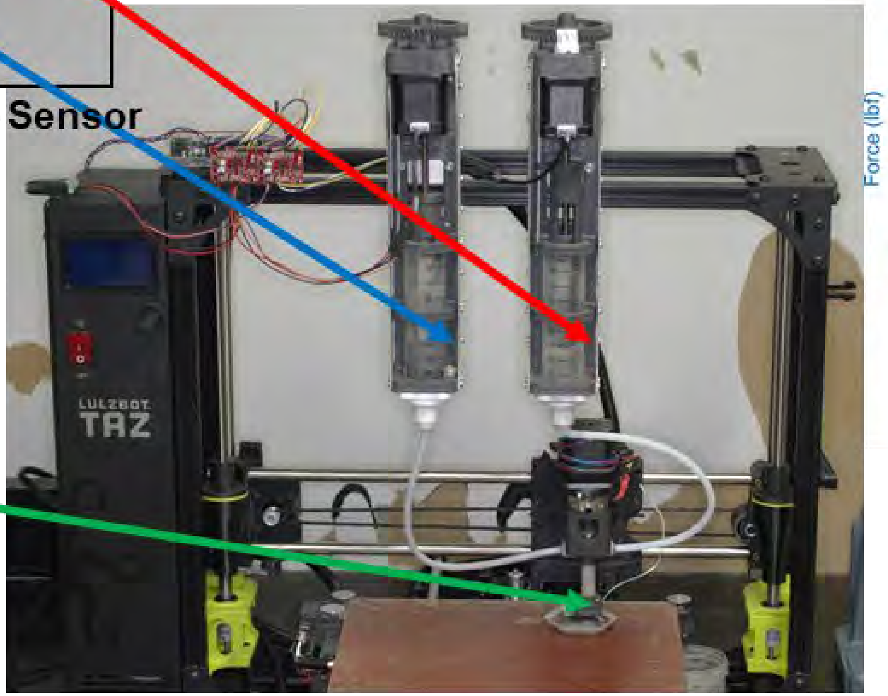
IN-SITU MONITORING – PRESSURE SENSORS

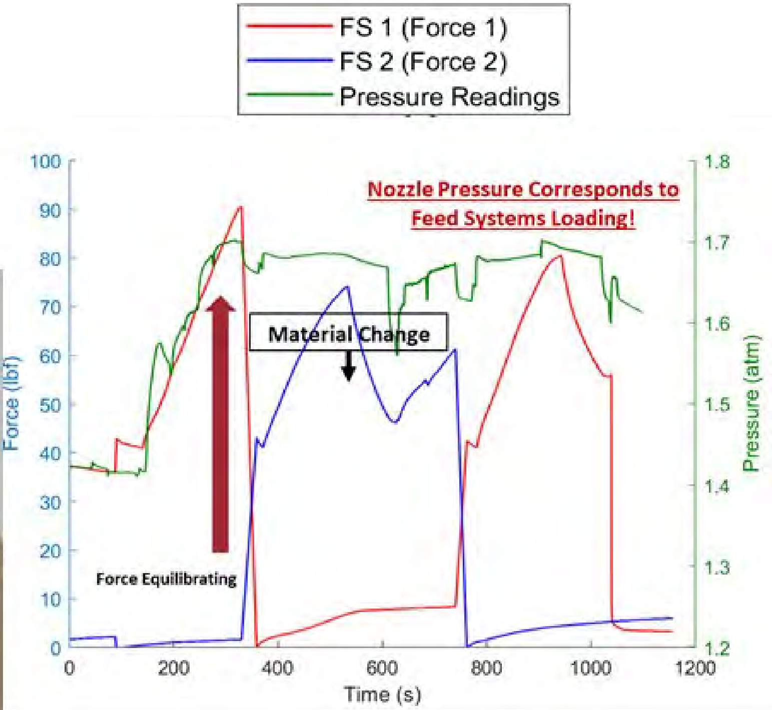
Monitor material delivery and increase control over composition changes



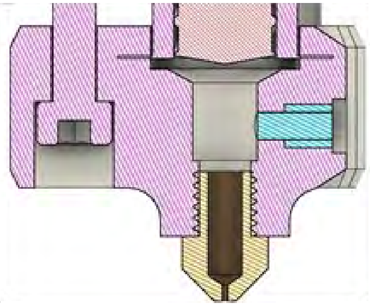
Feed System Pressure Sensor

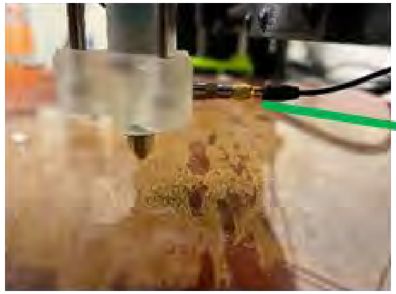
Modified DIW System for AM of Heterogeneous Ceramics





Monitor material extrusion and flow conditions at the nozzle





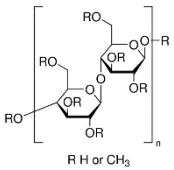
Nozzle Pressure Sensor

Allows for smoother material changes, reducing print failures and material waste

DIRECT-INK-WRITE AM PROCESS OVERVIEW

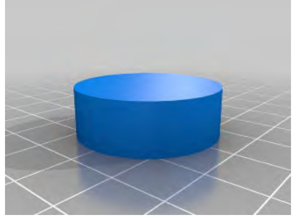
Addition of:
- Ceramic powder
- Binder
- Dispersant
- Acid
- Water

Methylcellulose (Binder) Gelation



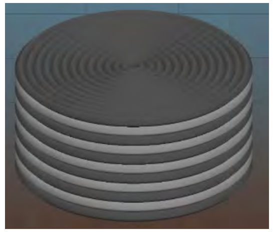
High Shear Mixing

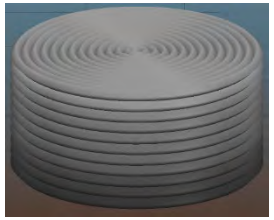
3D Model Design (.stl)



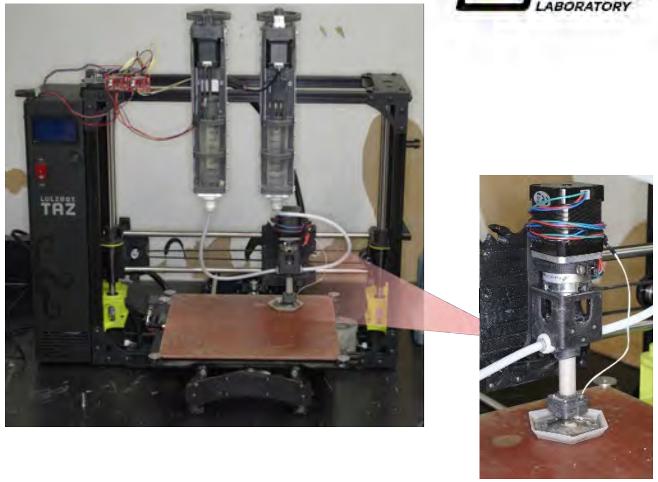
Toolpath Programing (.gcode)

Composition Incorporation

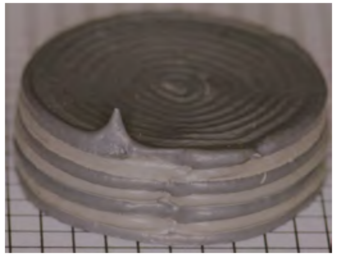


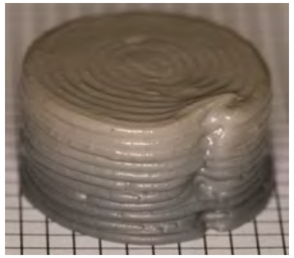


DIW Printing



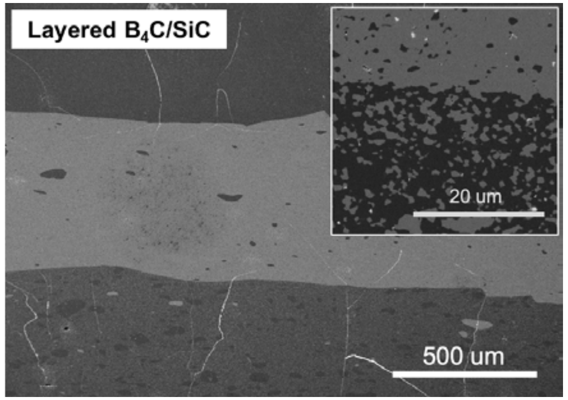
Drying





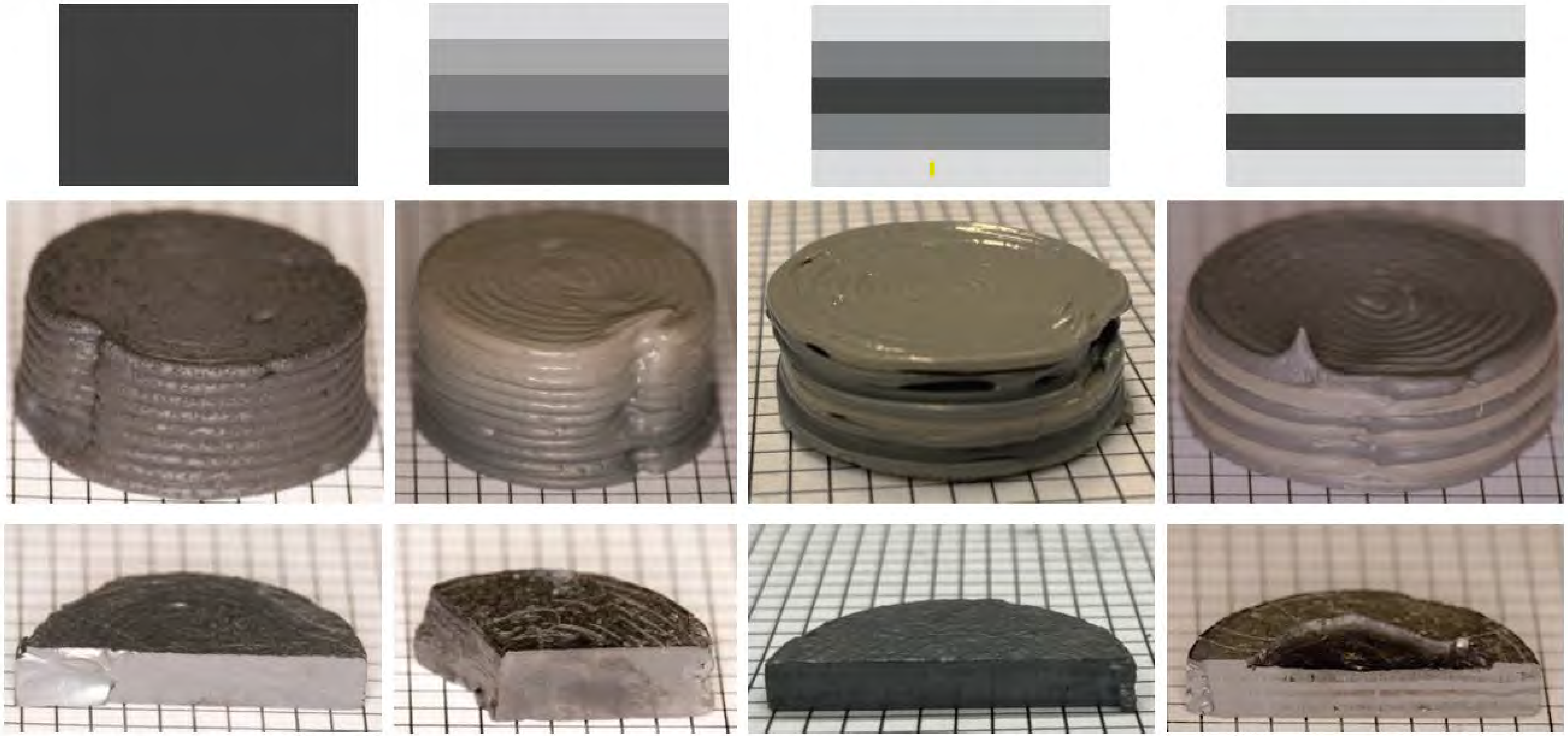
Binder Burnout

Sintering



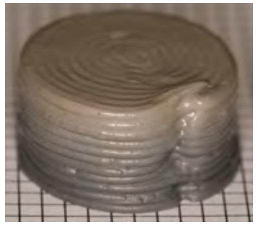
ENABLING CERAMIC DESIGN THROUGH DIW

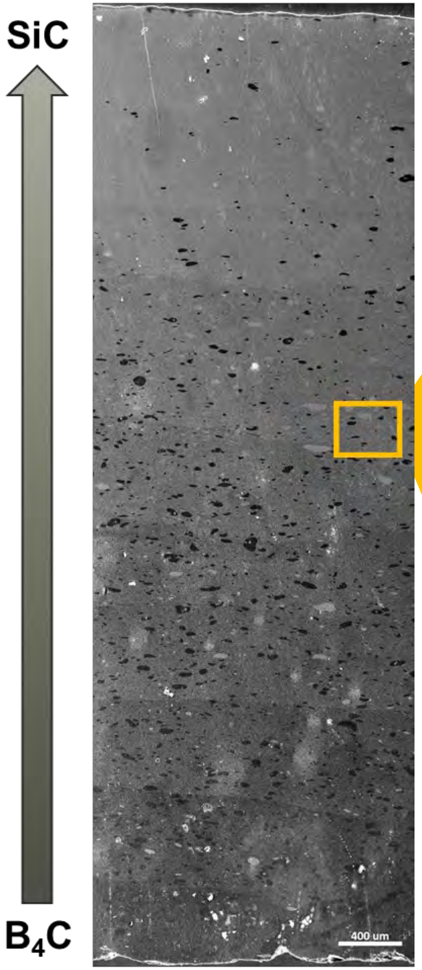
Demonstrated printability and densification for monolithic, graded, and layered ceramic structures not achievable through conventional manufacturing

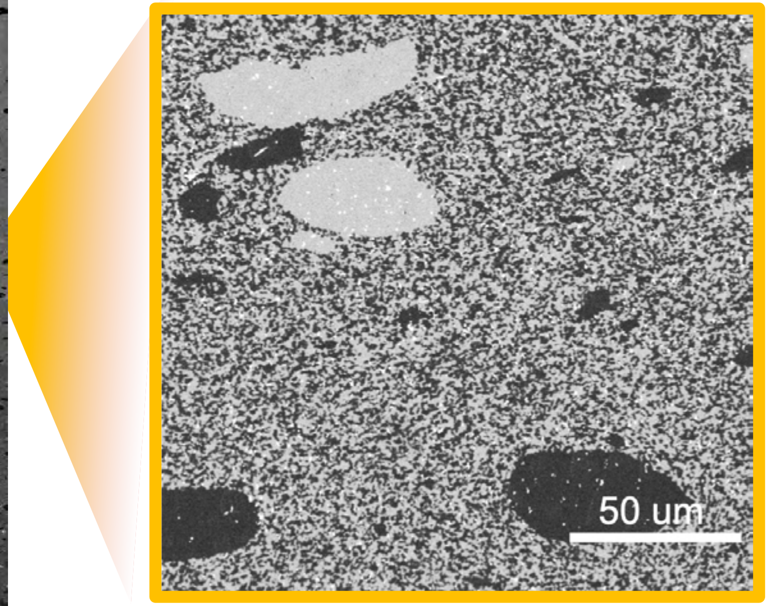


MULTISCALE CERAMIC DESIGN – MESO- TO GRAIN-SCALE

Continuous Gradient

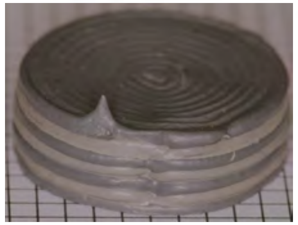




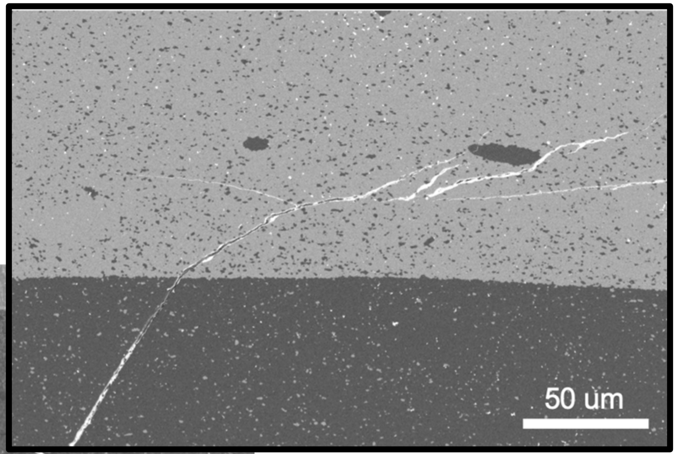


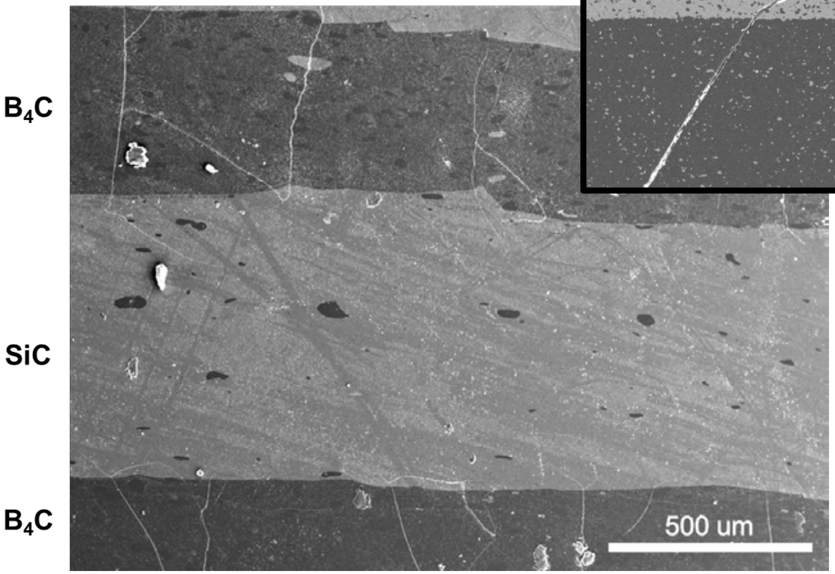
- Mesoscale composition gradient
- Microscale inclusions
- Grain-scale mixing

Discrete Layers



- Residual stresses from thermal processing
- Cracking in B_4C layers
  - B_4C in tension
  - SiC in compression

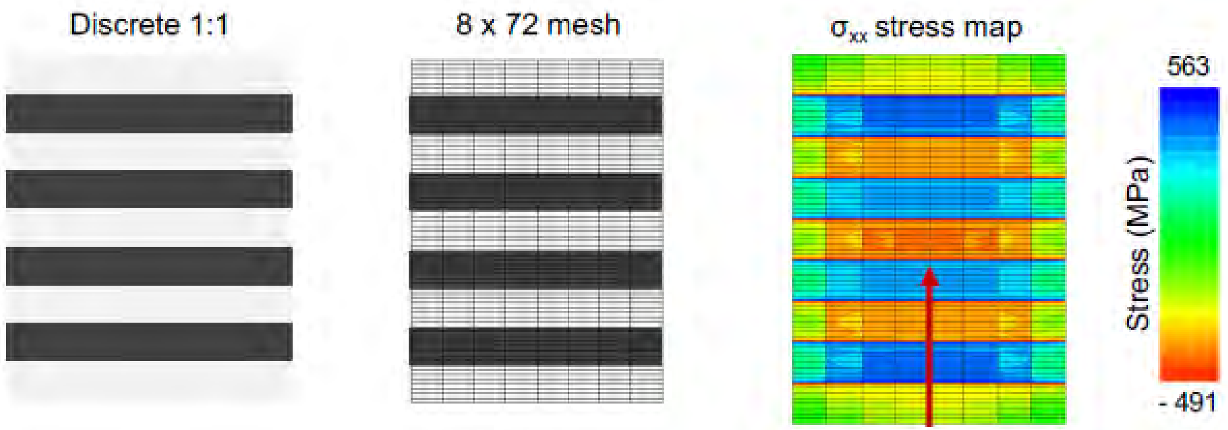


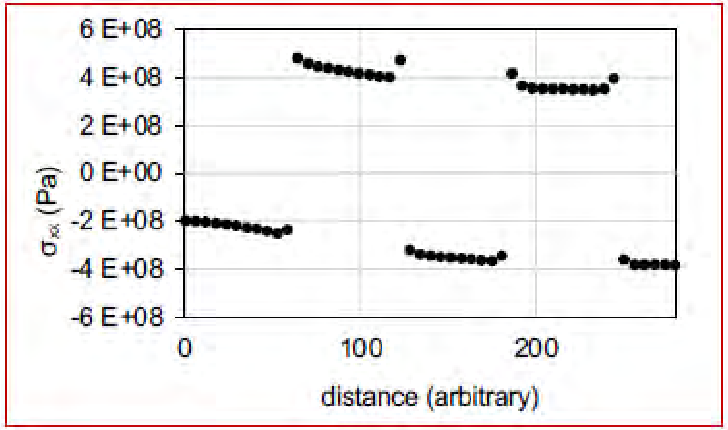


Crack bifurcation due to compressive stress in SiC

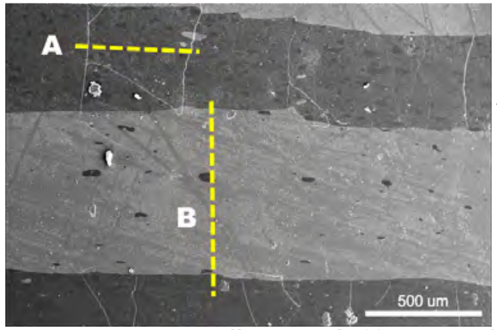
Ability to tailor composition, impedance, stress state into the ceramic and multiple length scales

ENGINEERING OF RESIDUAL STRESSES



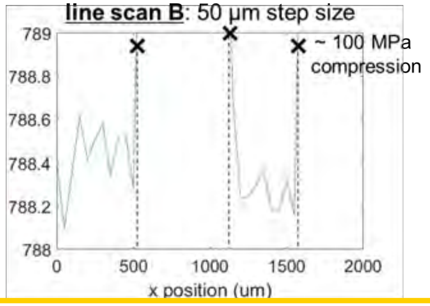


Residual stresses in a design can be *predictively modelled* using part geometry, elastic/thermal material properties, and processing conditions



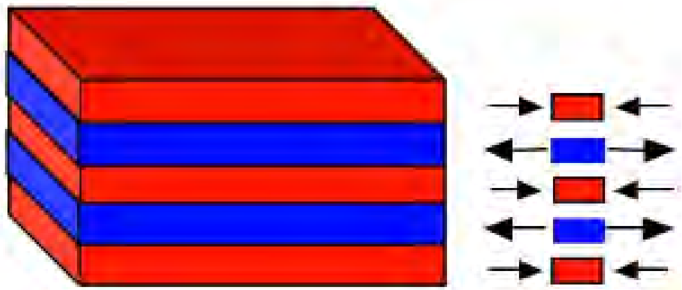
Residual stress can be *spatially measured* using Raman spectroscopy

- B_4C layers under tension
  - Stress relieved near cracks
- SiC layers under compression
  - Compressive region localized near interface



End Goal: *Designing With Residual Stresses*

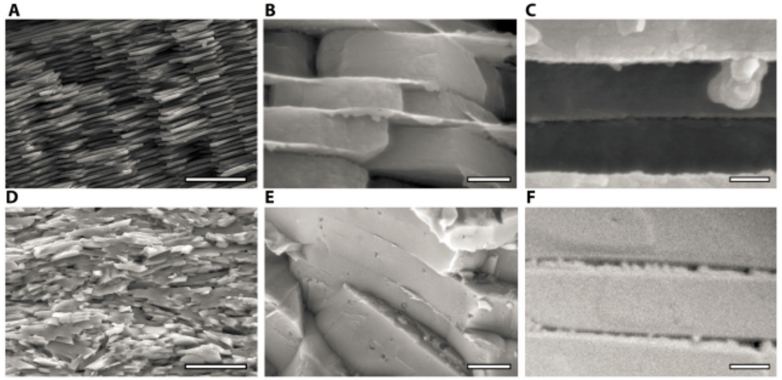
- Surface compression
  - Crack resistance
- Embedded compression
  - Crack arrest
  - Damage tolerance



Tools to provide confinement in armor through residual stresses at relevant length-scales

SLA FOR ENABLING CERAMIC TEXTURE TAILORING

Development of process science for tailorability of ceramic texture using passive and active alignment strategies



Bouville et al. "Strong tough and stiff bioinspired ceramics from brittle constituents, *Nature Materials*, 13, 508-514 (2014)

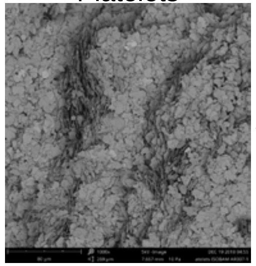
Hypothesis: Ceramics with high fracture toughness from microstructural texture will possess enhanced ballistic properties

Goals: Produce specimens with microstructurally enhanced toughness for testing

Approach: Leverage textured additive manufacturing of alumina as a rapid proof-of-concept process to evaluate hypothesis

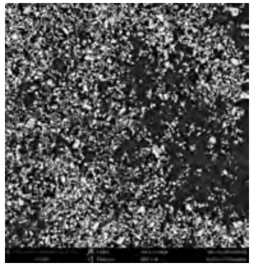
PROCESSING OVERVIEW:

Alusion Al_2O_3 Platelets

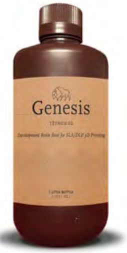


- α-Al_2O_3
- D_{50} = 7.9 µm
- Thickness = 0.2 µm

A16 Al_2O_3 Powder



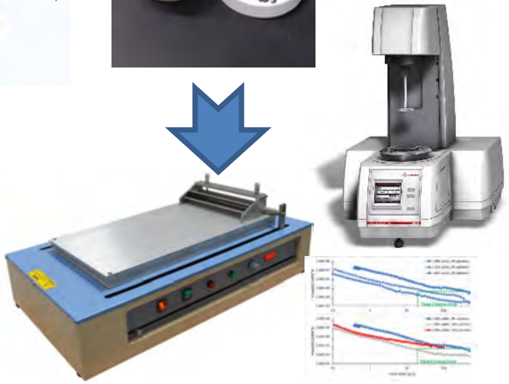
Tethon Genesis Photocurable Resin



Acrylate based resin cures in UV-A light

FlackTek Speedmixer

Feedstock

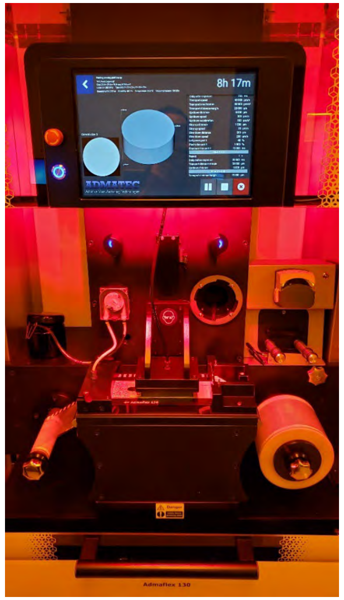


Tape cast & characterize

- Paste formulated using mixing methods developed for DIW
- High viscosity at high solids loadings limits platelet content
- Tape casting and rheometer used to characterize paste flow behavior

Print/Tape Cast Green Part

Research at ARL in collaboration with Rutgers University on Admaflex 130 printing system



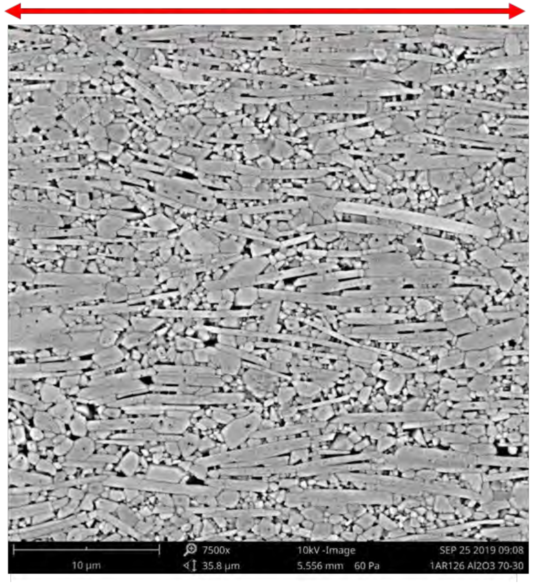
Sinter via hot pressing or pressureless route, characterize

GRAIN ORIENTATION IN TEXTURED CERAMICS

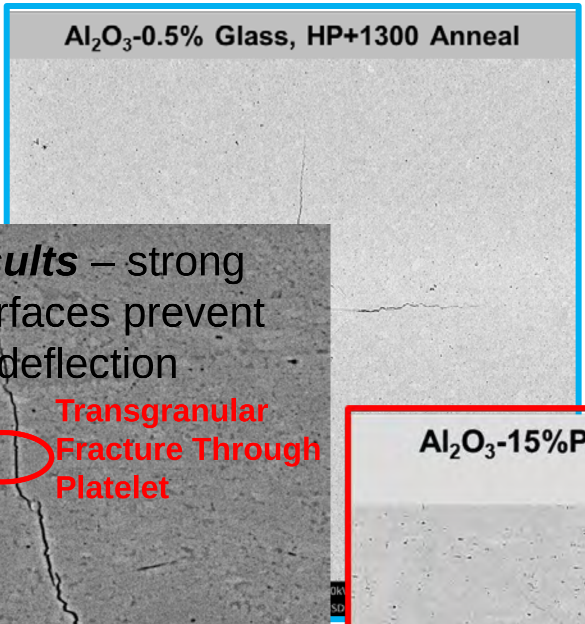
Development of process science for tailorability of ceramic texture using passive and active alignment strategies

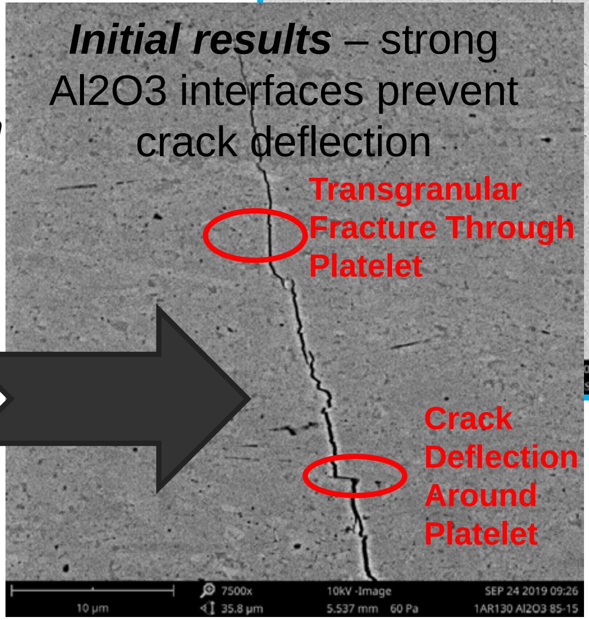
Demonstrated ability to texture ceramics using commercial ceramic AM equipment

- → ***Achieved full density after sintering***
- → ***Mimic the high-toughness structures observed in nature – bio-inspiration***
- → ***Ability to tailor and tune ceramic alignment to design fracture-toughened ceramics with changing properties through the part geometry***

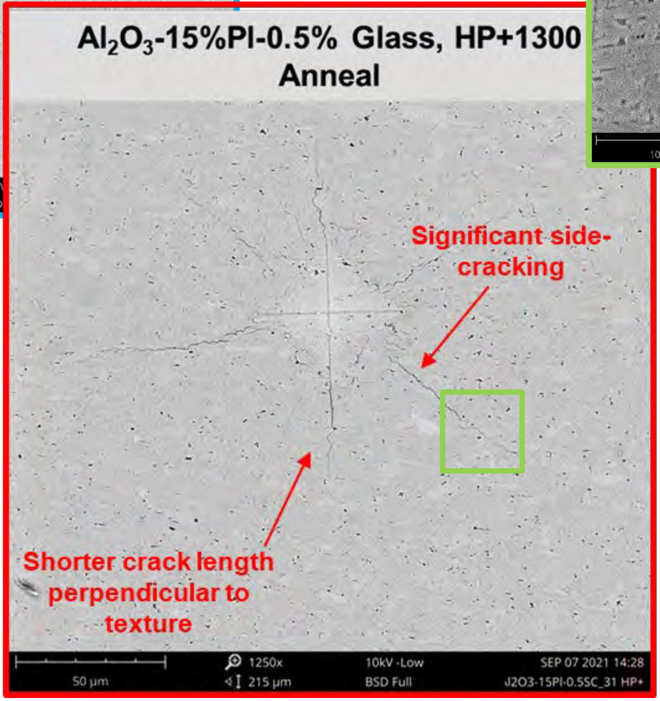


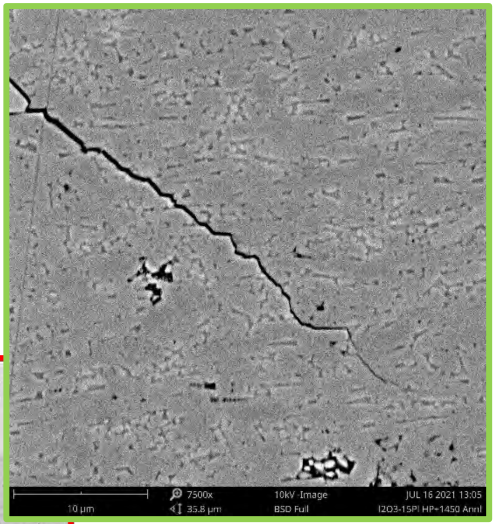
Initial results – strong Al2O3 interfaces prevent crack deflection



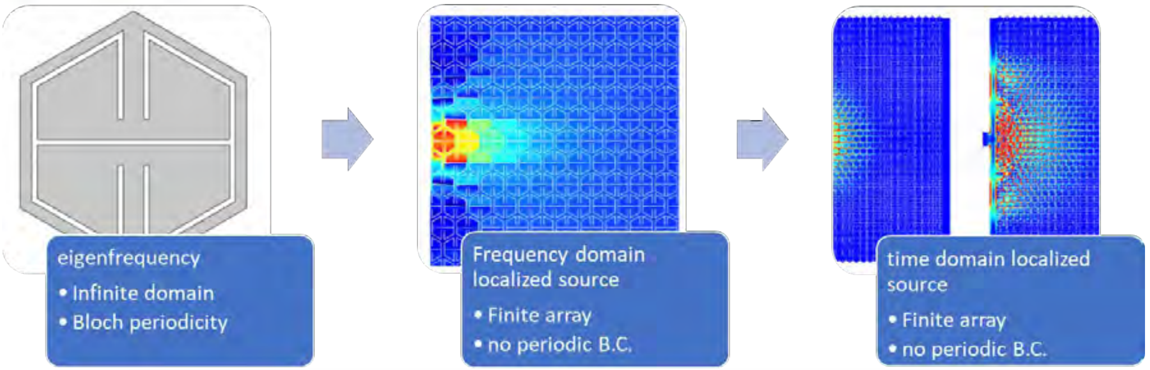


Current Focus: introduce grain boundary phases to promote toughening mechanisms





AM-ENABLED DESIGN OF POTENTIAL ENERGY MITIGATION



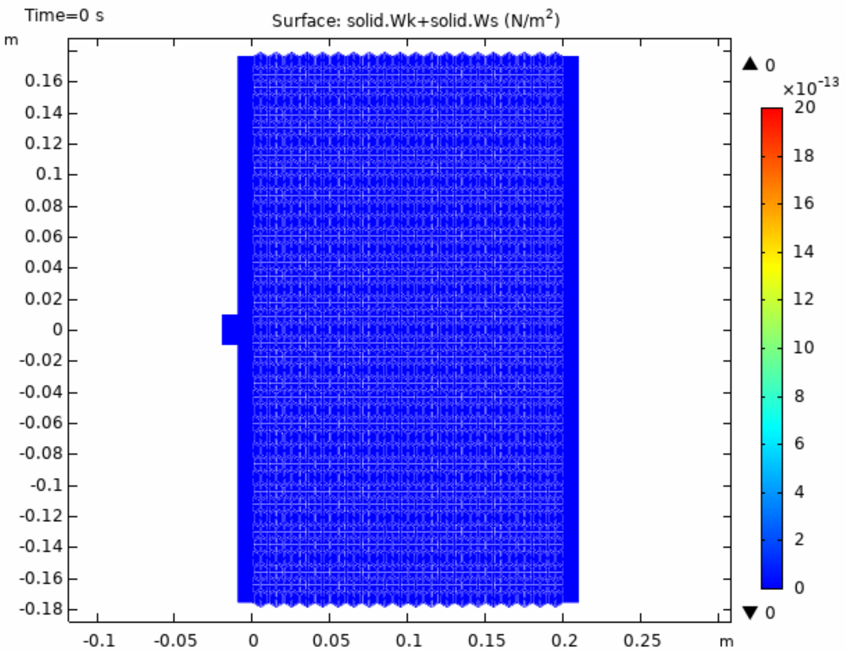
Alireza Amirkhizi (UML Mech. Eng.)

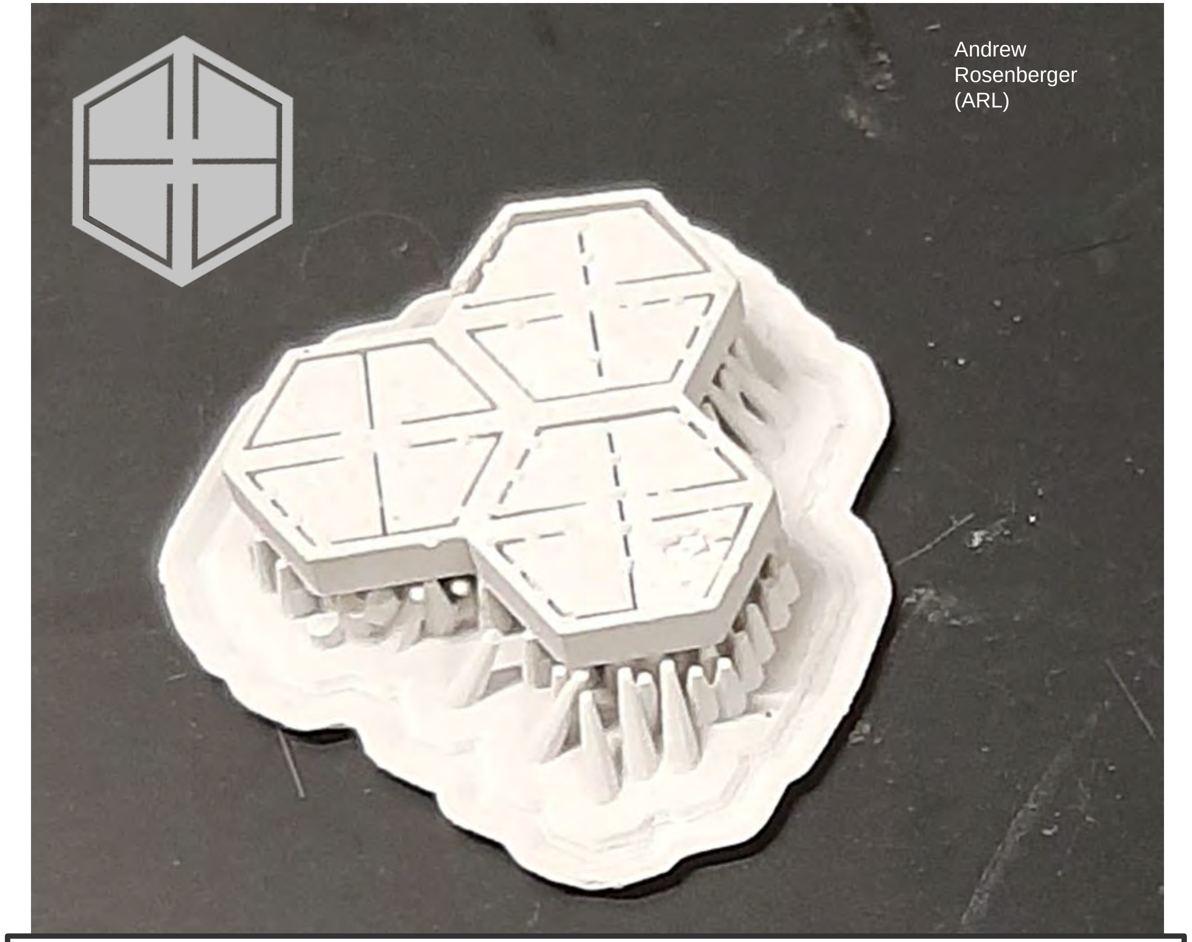
Reza Abedi (UTK Mech. Eng.)

Willoughby Cheney (UML)

Weidi Wang (UML)

Thomas Plaisted (ARL)





SLA technique allows for the validation of model-derived resonant structures for the reduction of energy loading during ballistic and blast events

UMass Lowell COMPOSITES

THE UNIVERSITY OF TENNESSEE KNOXVILLE

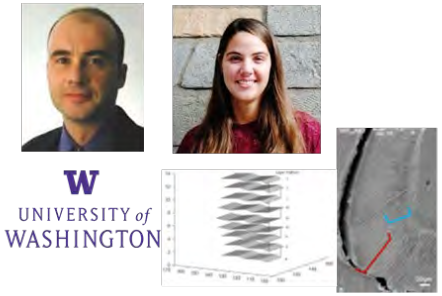
SPACE INSTITUTE AT TULLAHOMA

BUILDING RESEARCH ECOSYSTEMS – A FORCE MULTIPLIER

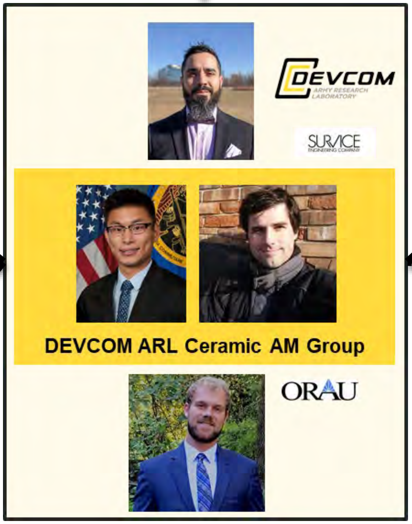
CERAMIC ADDITIVE MANUFACTURING RESEARCH

Stakeholder Coordination

CRADA: Direct-Write Additive Manufacturing of Dynamic-Network, Enamel-Inspired, Tough Ceramic Composites



UNIVERSITY of WASHINGTON



CRADA: Ceramic Synthesis and Processing Science for Armor

RUTGERS School of Engineering

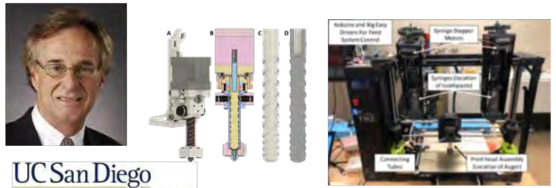
Academia/Industry/Government Partnerships: CRADA, (3x) AMMP Consortium Programs, Technology (2x) Assessment Programs, SBIR/STTR, Communities of Interest)

NATIONAL CENTER FOR MANUFACTURING SCIENCES

UNIVERSITY OF DELAWARE

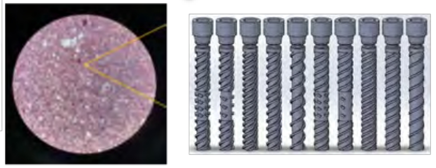
KRAETONICS

CRADA: Additive Manufacturing for Hierarchical Design in Next Generation Armor



UC San Diego
JACOBS SCHOOL OF ENGINEERING
Mechanical and Aerospace Engineering

USMA CME Senior Capstone: 3D Printing with Ceramics
Advisor: LTC Margaret Nowicki



LITHOZ

Technology Assessment & Transfer, Inc.
A DIVERSIFIED ADVANCED MATERIALS RESEARCH AND DEVELOPMENT COMPANY

ExOne

END OF PRESENTATION