Project: mat185

2021 DOE Vehicle Technologies Office Annual Merit Review

Additively Manufactured Interpenetrating Composites (AMIPC) via Hybrid Manufacturing

** Task 3A2 under the Powertrain Materials Core Program (PMCP)*

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Bridge to the future for medium and heavy-duty vehicle propulsion

VTO Powertrain Materials Core Program

3 National Labs, 30+ researchers, 4 Thrust Areas, 17 Tasks

Oak Ridge National Laboratory
Pacific Northwest National Laboratory
Argonne National Laboratory

THRUST 1.
Lightweight Alloys
(200 - 550°C)

THRUST 2.
Cost-Effective, Higher Temperature Alloys
(550 - 1000°C)

THRUST 3.
Additive Manufacturing for Advanced Powertrains

TRL 1 — Accelerating Development of Powertrain Alloys — TRL 4

Supported by Adv. Characterization & Computation

THRUST 4.

- Atom Probe
- Synchrotron
- Microscopy
- Neutrons

- ICME
- Thermodynamics
- Modern Data Analytics
- High Performance Computing

$30M/5 years launched in FY19

Task 3A2 Overview: (AMIPC) via Hybrid Manufacturing

Timeline/Budget

- Task start: October 2018
- Task end: September 2023
- Percent complete: 50%
- **3A2 Budget**
  - **FY20: $205k** AMIPC
  - **FY21: $190K** AMIPC

Barriers and Technical Targets

- High energy impact for piston survivability of knock and SPI
- Conventional material property relations limiting material selection
- Heterogeneous material systems are promising technologies with further exciting opportunities for development

Thrust 3. Additive Manufacturing for Advanced Powertrains

3A. Fundamental Development of Lightweight Alloys for AM
3B. Development of Higher Temperature Alloys for AM

Task	Title	TRL	FY20	FY21
3A1	Fundamental Development of Aluminum Alloys for Additive Manufacturing	Low	$425k	$375k
3A2	**Additively Manufactured Interpenetrating Composites (AMIPC) via Hybrid Manufacturing**	**Low**	**$205k**	**$190k**
3A3	**NEW:** Fundamentals of Non-Equilibrium Processing	Low	$0k	$140k
3B1	Fundamentals of Austenitic Alloys via Additive Manufacturing	Low	$200k	$205k
3B2	Ferritic alloys for Heavy-Duty Piston via Additive Manufacturing	Low	$225k	$225k
	Subtotals		$1,075k	$1,135k

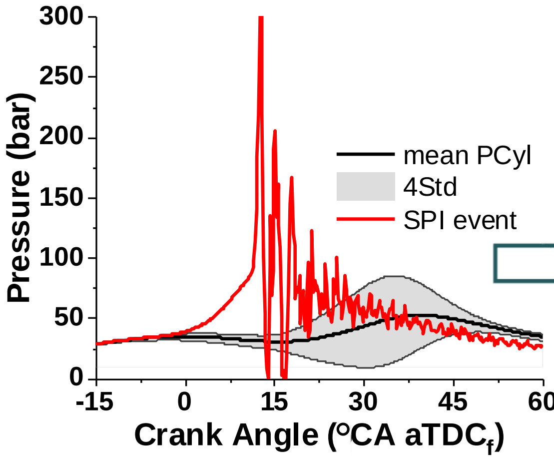
Partners

- Program and Task 3A2 Lead Lab
  - –Oak Ridge National Lab (ORNL)
  - –Thrust 4 (ORNL)
- Partners on Subtask 3A2 (this project)
  - –Task 3B1 (lattice material)
  - –Rice University
  - –Bechtel (broader AMIPC work)
  - –MIT
  - –Air Force Research Laboratory

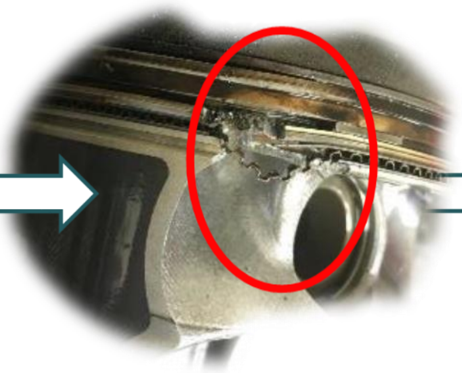
Project Aims to Address Piston Failure from Knock/SPI

- US O.E.M. USDRIVE roadmap shows increased reliance on high efficiency
- High load survivability of knock and Stochastic Pre-Ignition (SPI) in high-efficiency engines is lacking, in-field warranty issues from material failure
- Direct approach to produce multi-metallic components while enabling opportunities for lightweighting

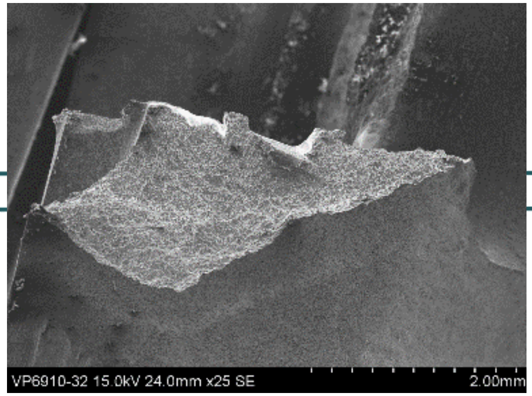
Abnormal combustion event



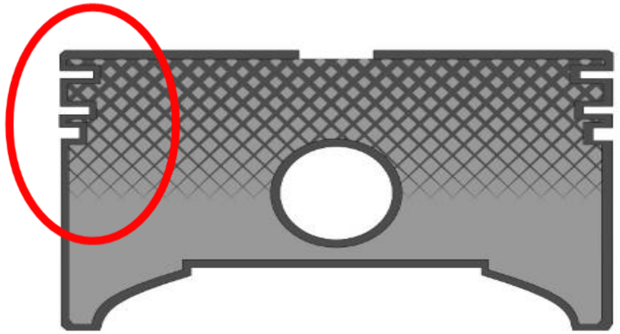
Broken Piston (knock & SPI)



Catastrophic failure (single event)



high energy absorbing material and manufacturing concepts



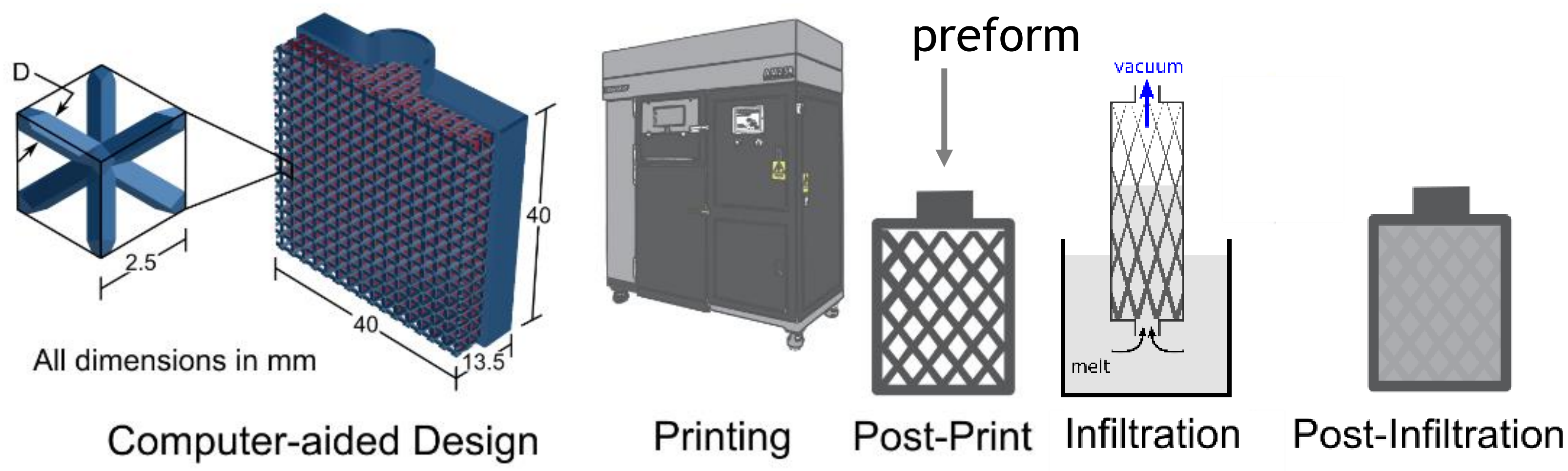
Milestones For 3A2

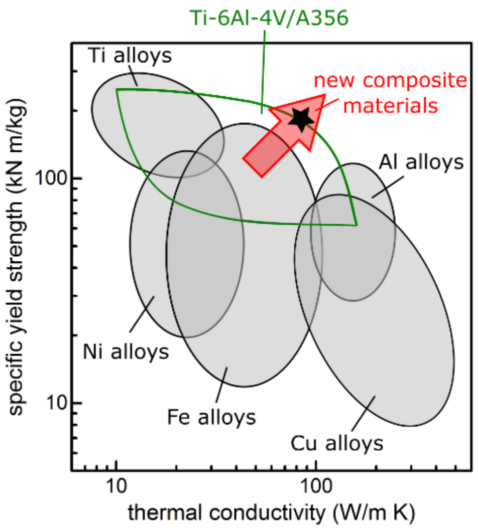
Milestone Name/Description	Planned End Date	Status
Quantify interface and mechanical performance of HIP and non-HIP Printcast materials through experimental and simulation and tools, including DIC tensile testing, report in Q2 quarterly.	End of **Q2**, FY21	**Completed**
FEA simulation of piston ring land comparing conventional piston material performance to that of PrintCast material system under relevant boundary conditions to LSPI, and report in Q4 quarterly.	End of **Q4**, FY21	**On-Track**

Hybrid Process Combining Additive Manufacturing (AM) & Melt Infiltration With Advanced Characterization at ORNL

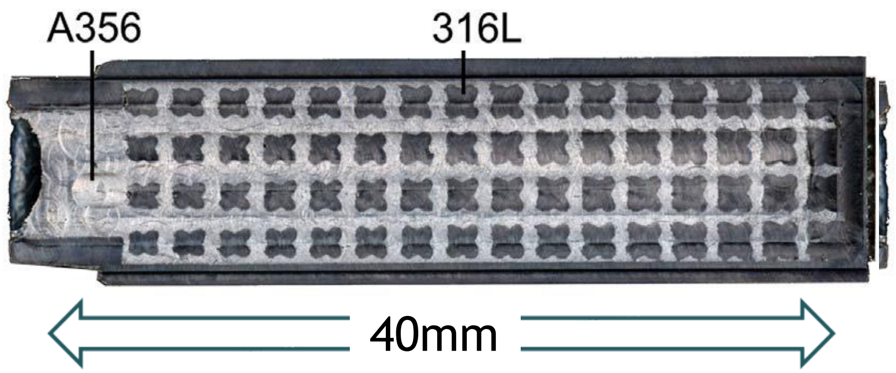
- AM reinforcement & preform
  - AM process enables design flexibility in placement, geometry, and material of reinforcement
- Infiltrate preform with lower melting temperature material
  - Vacuum melt infiltration used as surrogate for pressure die casting
- Approach enables accessing new material property regions with conventional alloys

Two step AMIPC processing approach





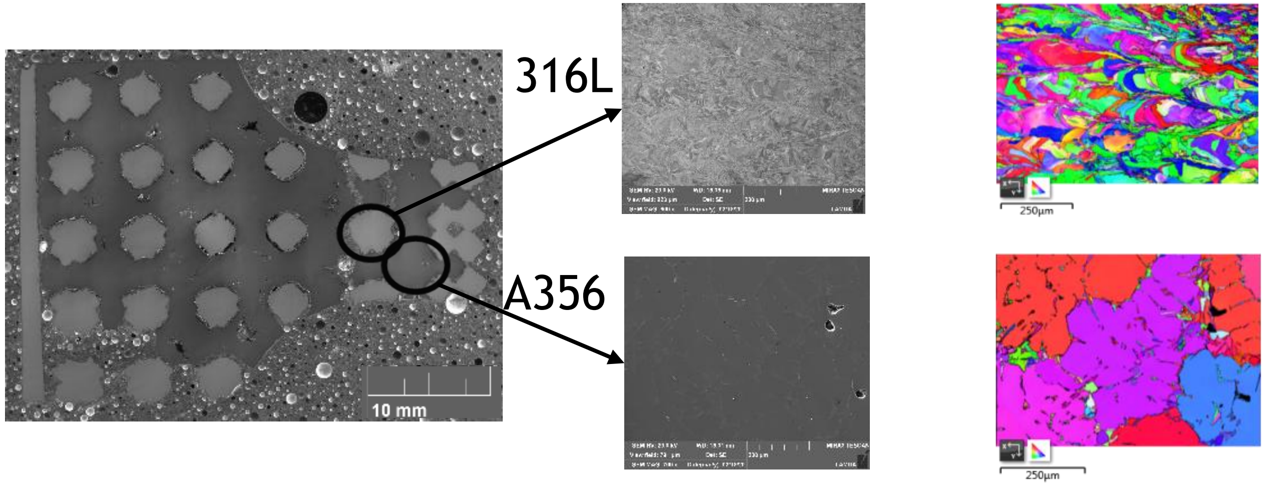
2-step approach enables local material variation (functionally graded material)

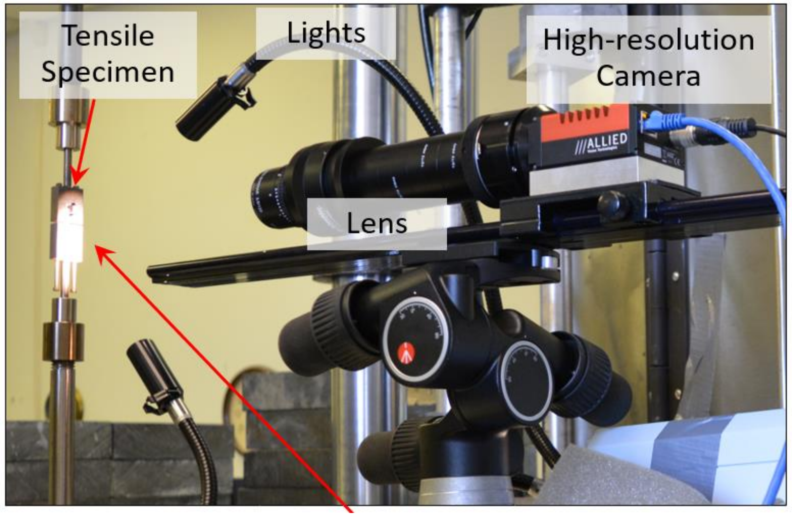


Tensile Testing Coupled with Digital Image Correlation Used to Improve Understanding of Constituent Behaviors

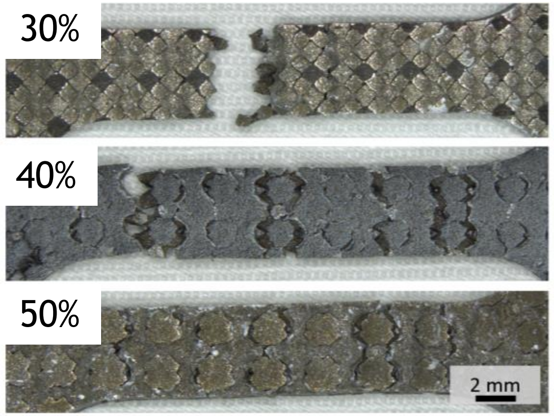
- Advanced characterization of microstructure and physics SEM, EBSD, EDS, XCT, DIC

load frame coupled with digital image correlation instrumentation and software

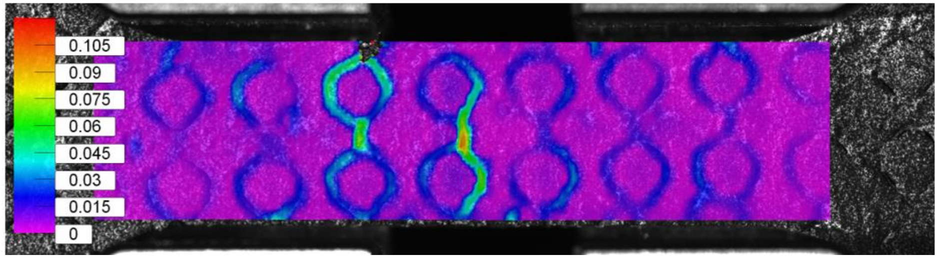




- Measurements directly analyzed while also informing simulation effort



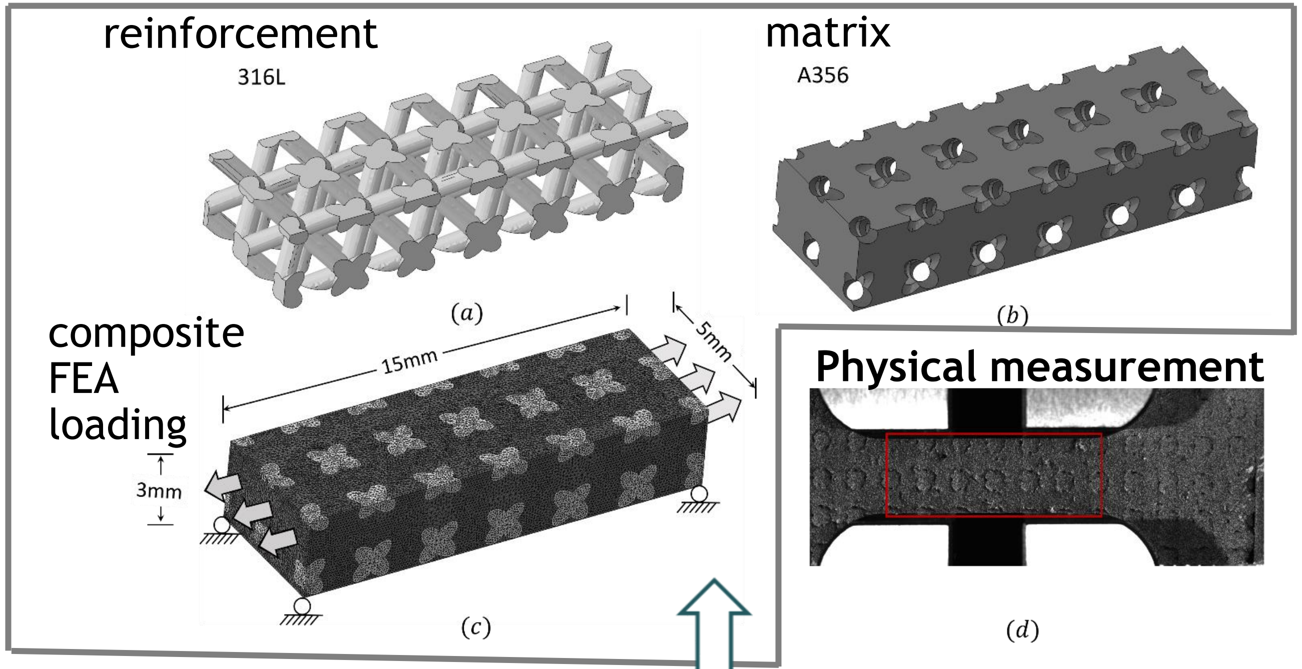
Digital Image Correlation



Commercial Software (ABAQUS) Modified to Enable Simulation of Constituents, Interface, and Impact

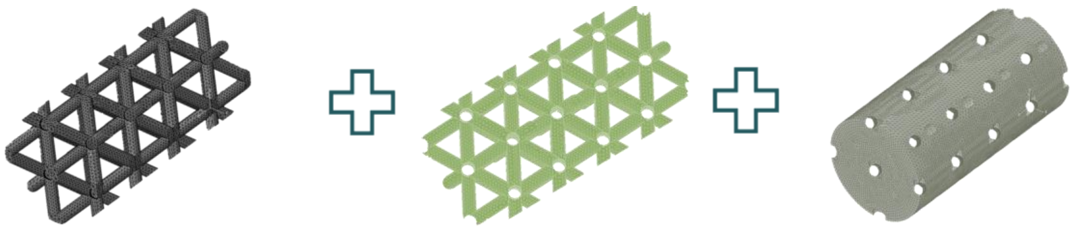
- Commercial software (ABAQUS) used to simulate tensile loading
- No cohesive bonding between constituents assumed, interface simulation tailored with measurements and literature
- Tensile loading validated model expanded to include impact and shock loading for damage tolerance simulations as calibrations for piston damage modeling

Model

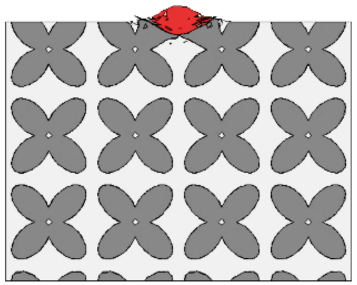


Interface modeled as appropriate

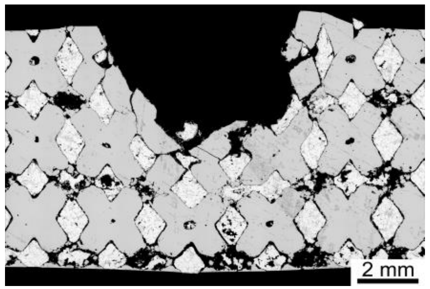
AM reinforcement | interface | Infiltrated matrix



Impact Modeling

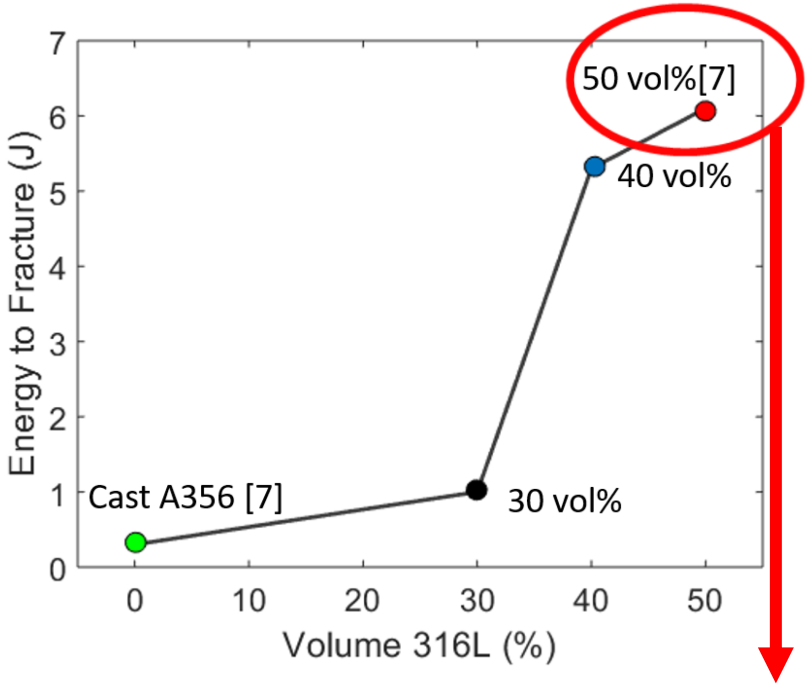


Physical measurement

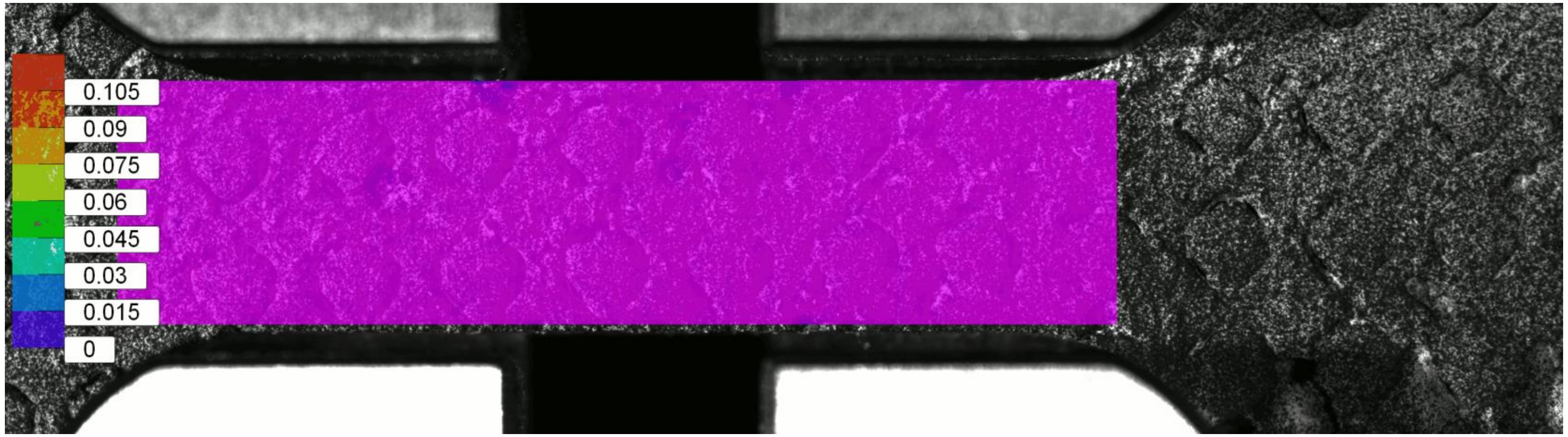


Transition to Delocalized Damage Enables Dramatic Increase in Energy Absorption

- Dramatic energy to fracture improvement (~5X) observed when delocalized damage occurs
  - DIC* measurements highlight that a multiple cracks occur in stages where failure points propagate across the domain as loading continues
- High damage absorption potential for extreme conditions



DIC measurement of tensile loading 50% volume fraction 316L SS/A356 BCC



**Differential Interference Contrast*

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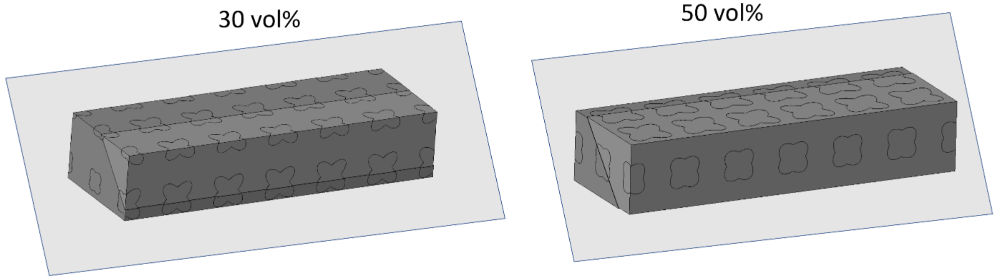
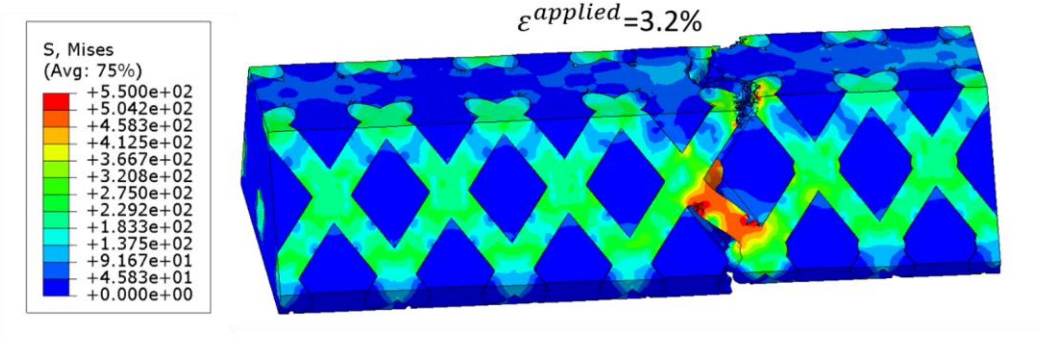
Sub-Surface FEA Results Highlight Source of Damage Transition

- Localized damage fails at a single node/location
  - Tearing observed in simulation
- Increased volume fraction (strut size) distributes load
- Significant bending load on lattice at nodes

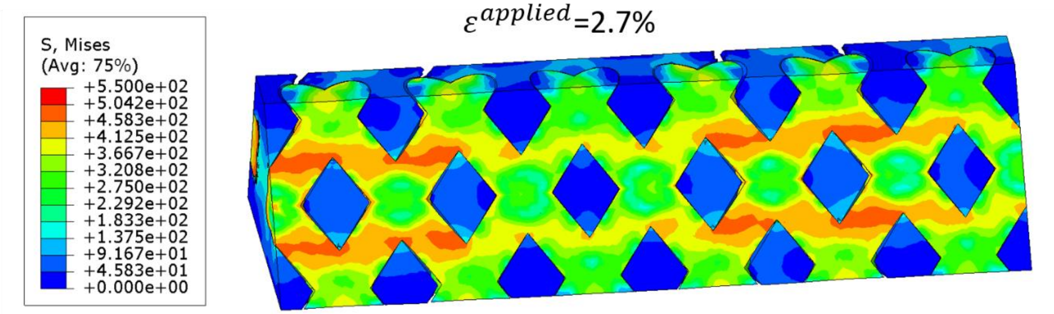
"slice" through FEA domain



30% volume fraction 316ss (localized failure)

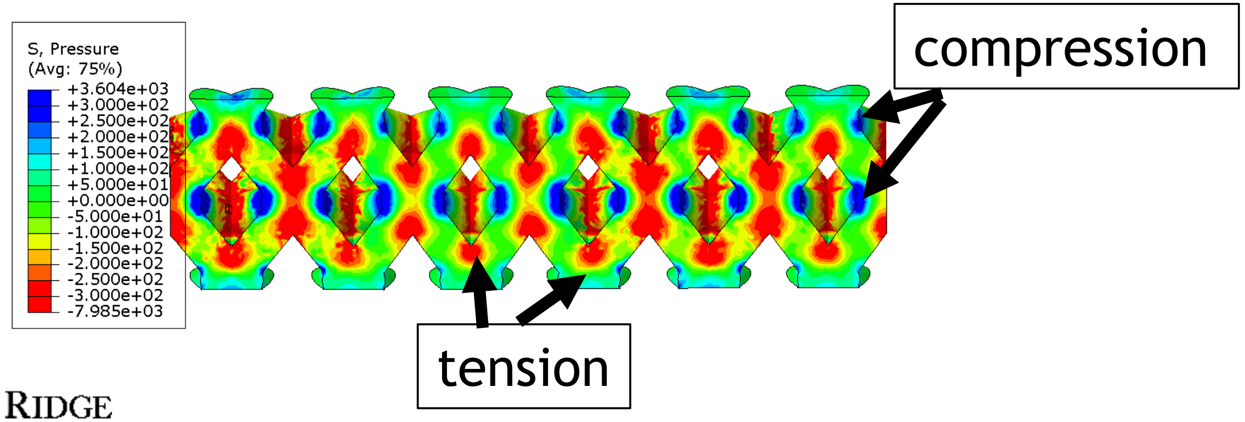


50% volume fraction 316ss (delocalized failure)



Pressure calculated in FEA

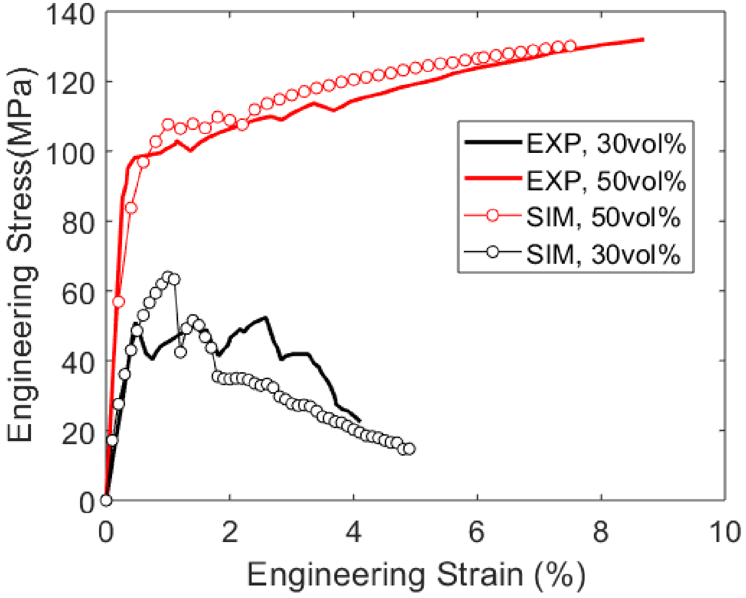
50% volume fraction 316ss (delocalized failure)



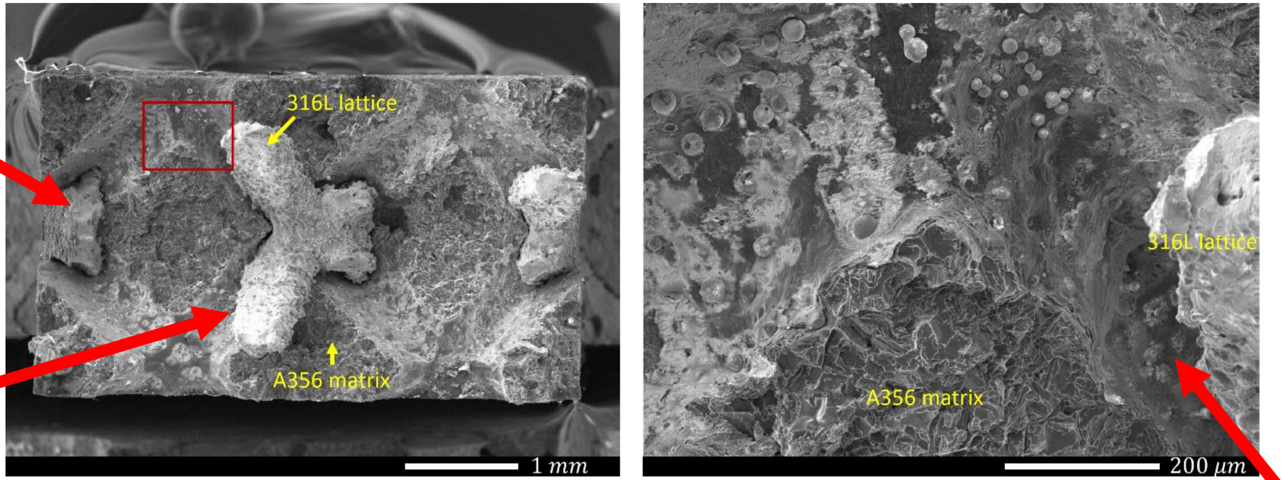
Cheng et al., *Materials & Design* (2020)

SEM Measurements Confirm Delocalized Failure Occurs at Node/Strut interface

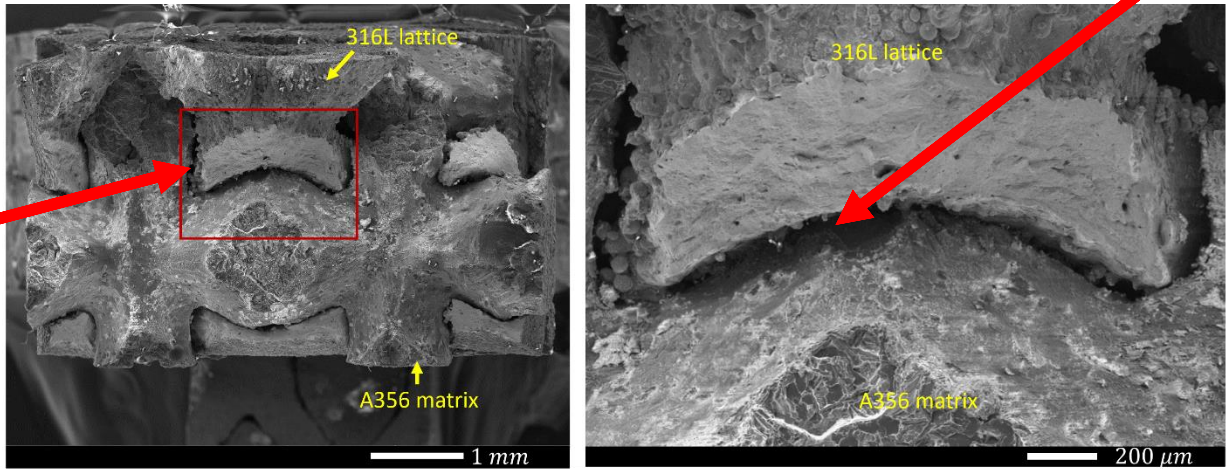
- Failures at nodes
- Detached matrix/strut interface
- Smooth shear of matrix material



30% volume fraction (localized failure)



40% volume fraction (delocalized failure)



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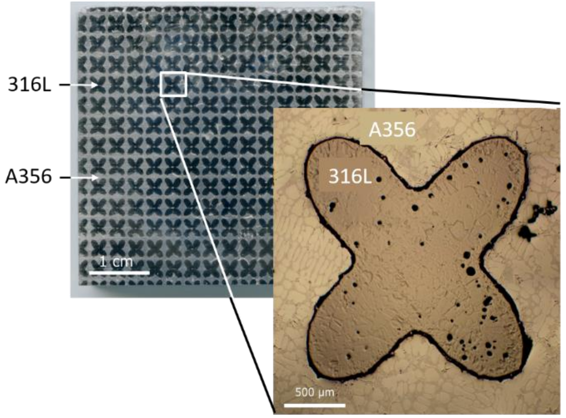
HIP post-processing closes pores in A356 and reduces interface gap significantly, reinforcement untouched

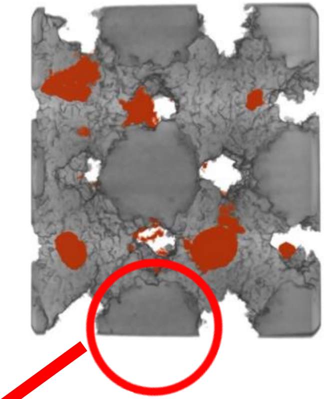
- HIP 30% AMIPC at ASTM F3318 – 18 conditions
  - (100 MPa at 510-530°C for 3 hours)
- HIP effectively closed interface gap in samples

As-cast AMIPC has pores at interface, in matrix and in reinforcement

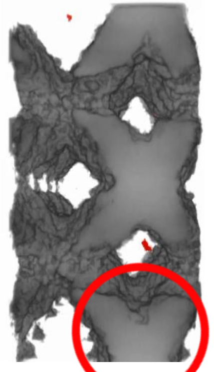


XCT results show HIP reduces pores in A356, no effect on 316

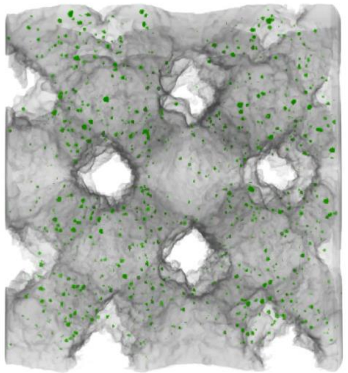
As-cast A356 pores (red)



Post-HIP A356 pores (red)

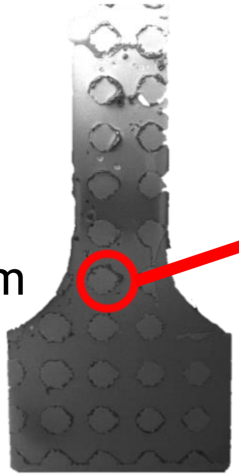


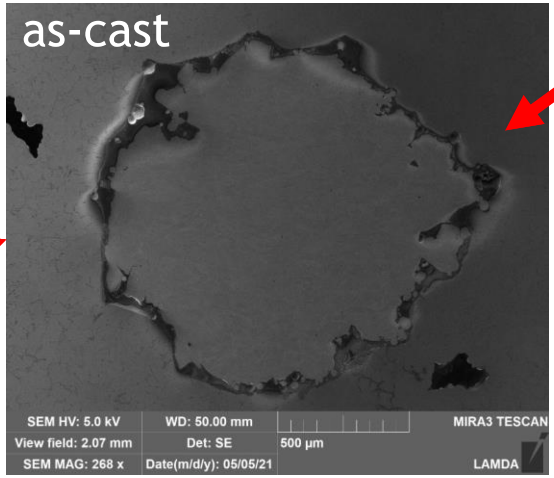
316L pores (green) (HIP=no change)



SEM results of as-cast interface between 316L/A356 shows significant debonding

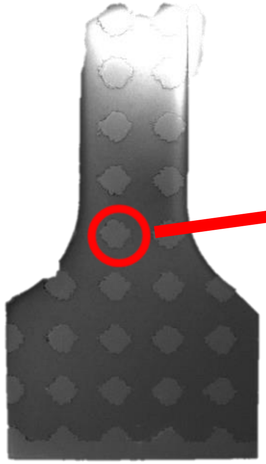
- gap ~50-100 μm

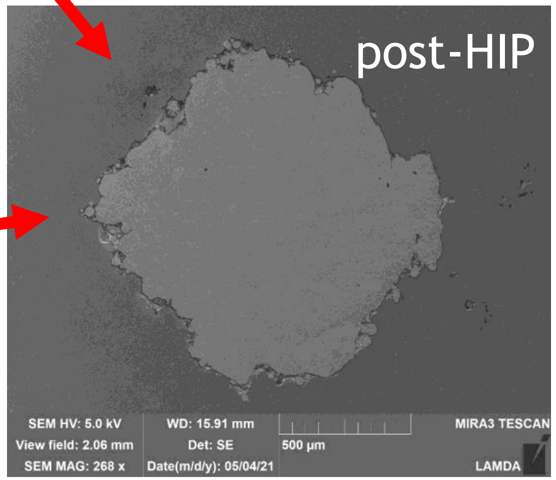




Post-HIP interface between 316L/A356 shows strong bonding

- ~no gap





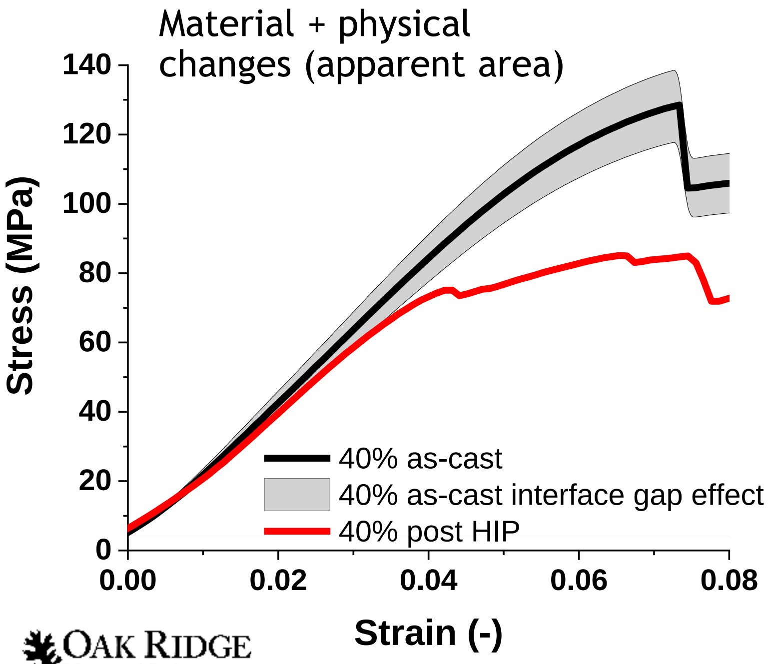
HIP dramatically reduces intra-matrix porosity and interface gap, but effect on performance was negative

Interface bonding directly affects mechanical performance

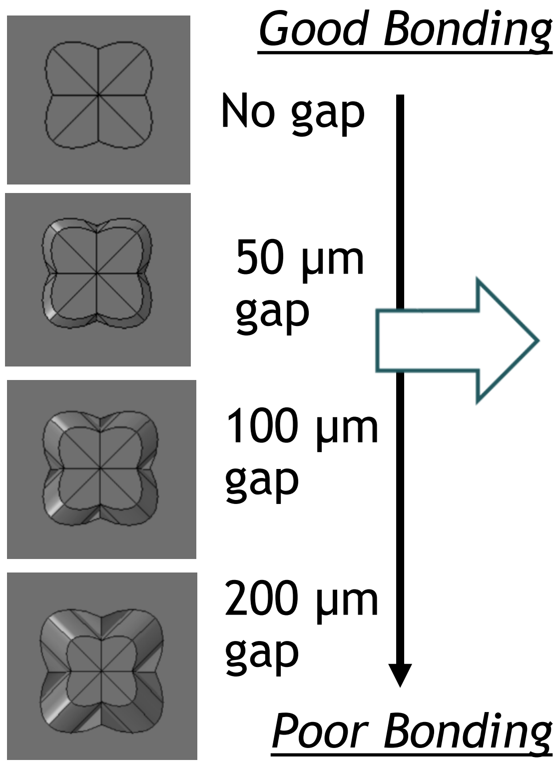
- As interface is removed, strength and ductility increase
- Strong bonding reduces energy absorption potential

FY20 neutron diffraction results showed that in delocalized damage A356 placed in compression when 316L in tension, gap is seen to be critical

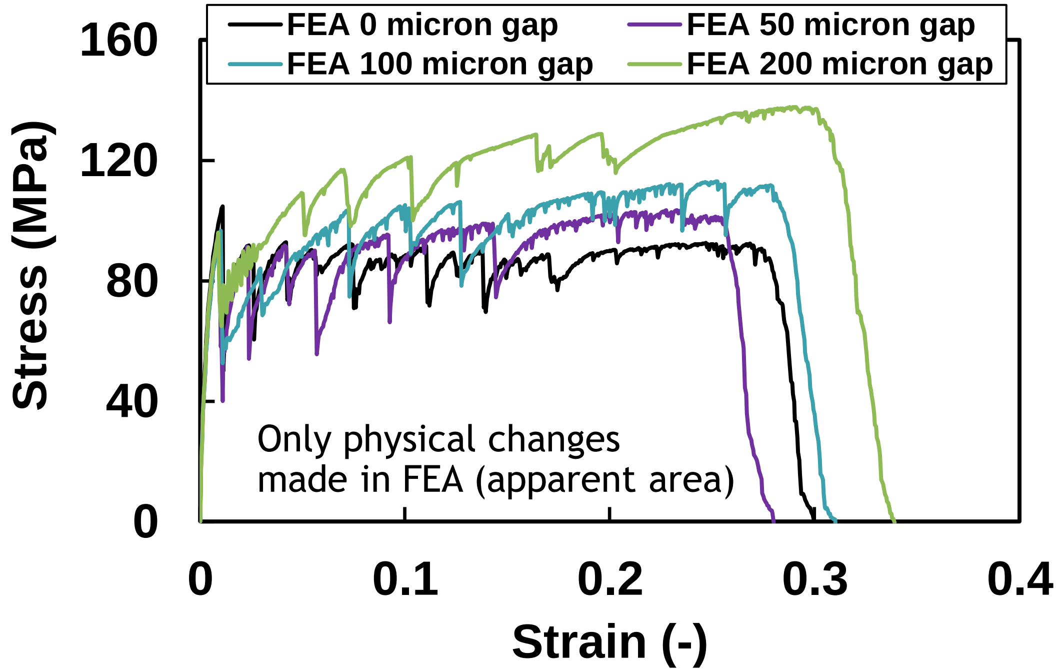
physical measurement



CAD model of bonding

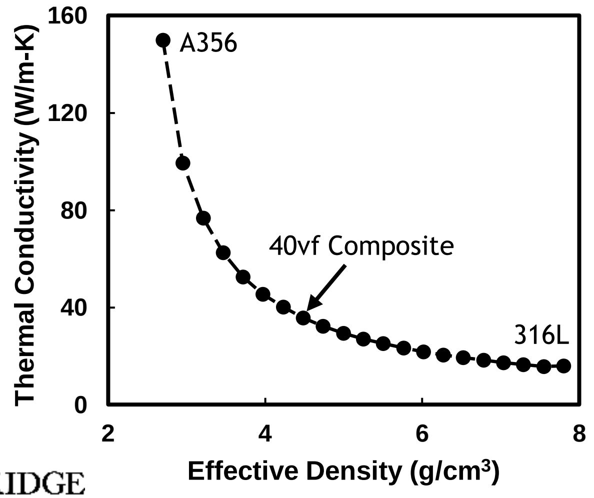


calibrated FEA simulation of bonding

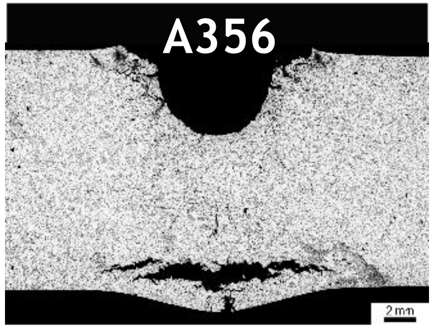


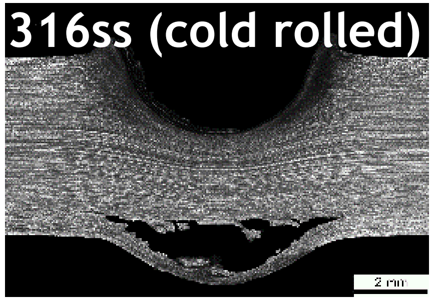
Damage Tolerance Measurements and Modeling Show Significant Performance Improvement on Impact

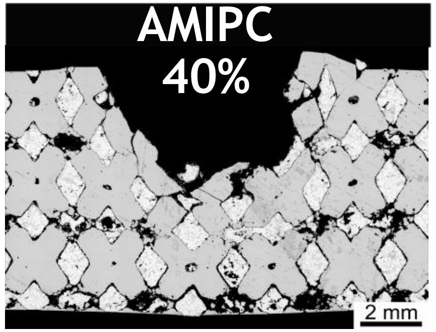
- Aluminum flyer at 6.1 kM/s (~Mach 18) impacting surface at room temp. and press.
- Conserve mass (Δ thickness)
- Improved survivability of AMIPC (no/little spalling)
  - Improved thermal conductivity vs 316L (critical for pistons and battery protection)



Measurements RICE

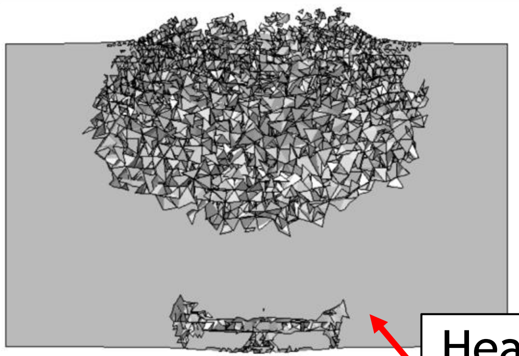






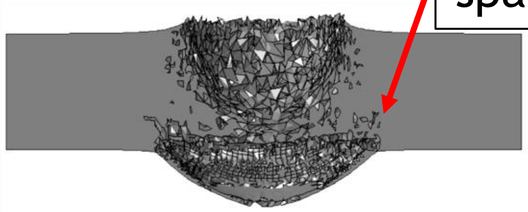
Simulations

A356
Thickness: 12 mm
Rho=2.7 g/cc
K=151 w/m²-k

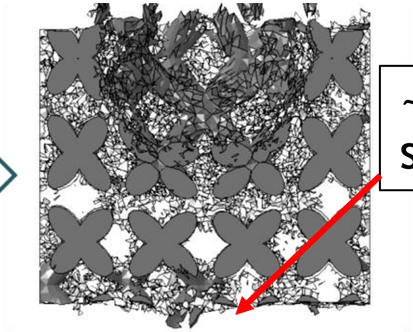


Heavy spalling

316L
Thickness: 4.5 mm
Rho=7.8 g/cc
K=16.3 w/m²-k



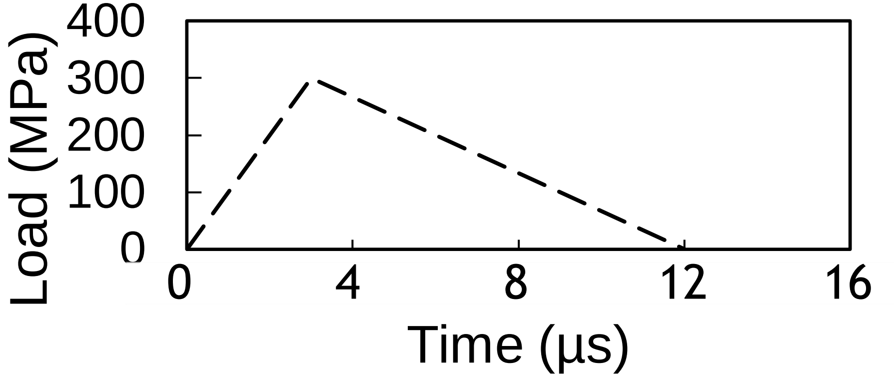
AMIPC (40%)
Thickness: 7.5 mm
Rho=4.7 g/cc
K= 32.4 w/m²-k

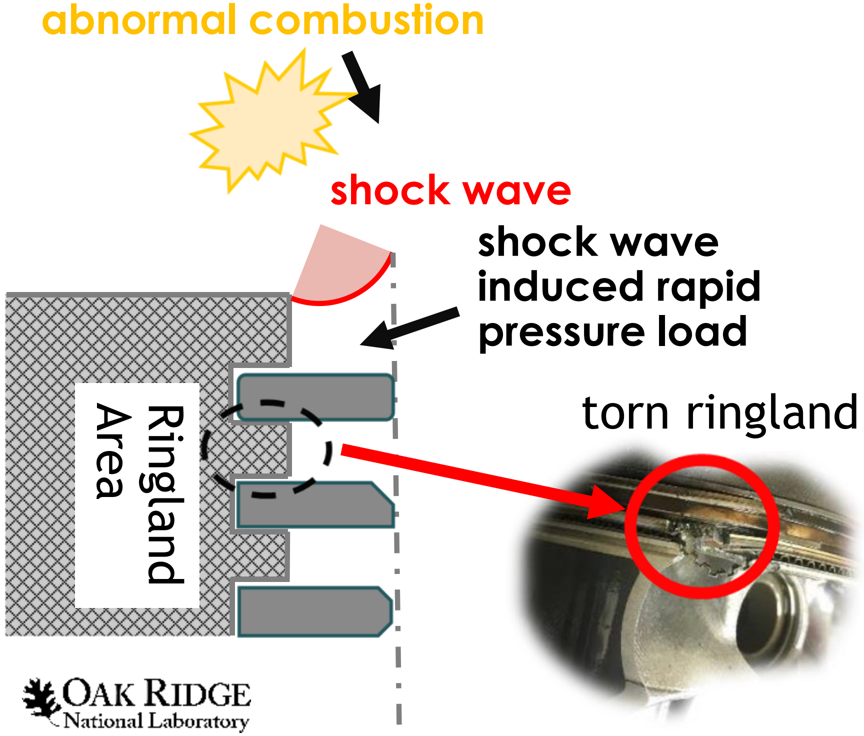


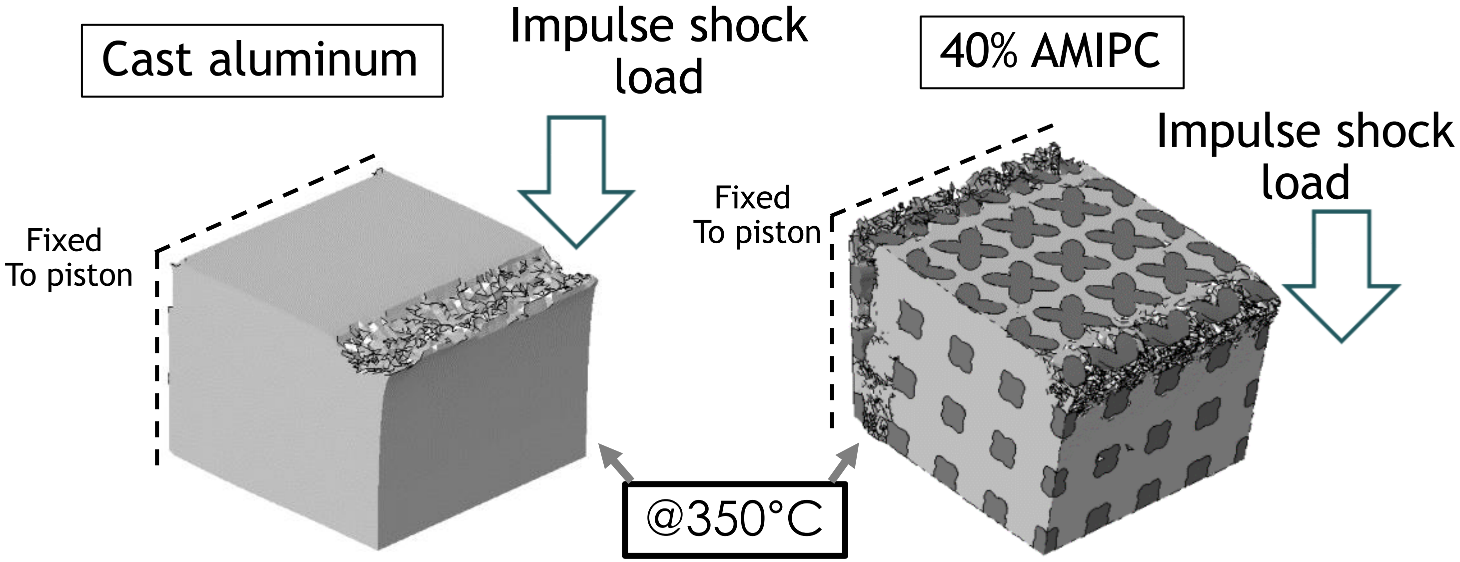
~no spalling

Initial simulations of abnormal combustion induced shock loading highlight improvement using AMIPC structure

- Tensile bars harvested from cast aluminum piston and loaded at range or temperatures for calibration
- Experimental conditions of SPI and literature assessment used as shock loading impulse (include shock reflection amplification in simulation)







Delamination and full tearing **after ~8 µs (failed) (~0.1°CA @2000 rpm)**

No delamination or tearing **after ~60 µs (not failed) (~0.7°CA @2000 rpm)**

FY20 reviewer comments suggest program is on-track, on target, future work should target failure mechanisms, CAD/FEA simulation, fatigue, and system level designs

R: …this project supports the overall DOE objectives by providing the knowledge needed to develop high performance materials for lower cost, higher efficiency engines and vehicles.

A: Thank you, the research team anticipates that several sectors could benefit from this technology

R: The team is demonstrating extremely good progress in the overall presentation of this novel material system for pistons… the future work component is exciting to consider

A: The research team is focusing on opportunities and refinement of the material system

R: The reviewer would like to know if excellent energy absorption makes this material good for structural components to improve crash worthiness.

A: The FY21 results of hypervelocity impact suggest that AMIPC could greatly benefit crash worthiness and impact/energy absorption designs

R: Obviously, the approach is successful given the improvements, but without more discussion of the underlying science, it is hard to determine whether or not the results are truly optimum…

A: FY21 efforts have focused on understanding the science and failure processes, optimization is evolving

R: More emphasis on the failure modes would be extremely instructive….to initiation mechanisms and propagation, although this would appear to be addressed in detailed fashion through the high quality FE simulations.

A: This has been a significant focus in FY21 efforts, we believe that the current results are on track to help understand these processes through DIC and FEA coupling

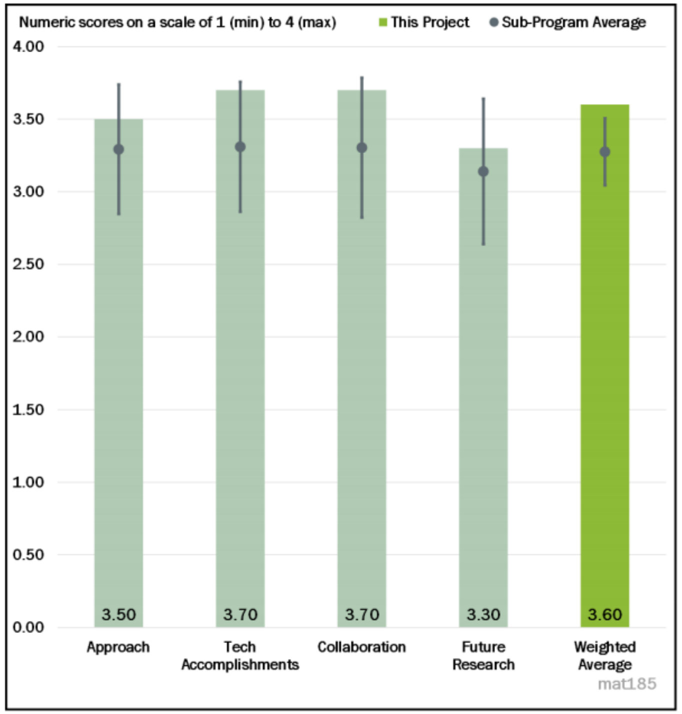
R: The reviewer noted that bonding of molten Al with 316L is generally poor so there will essentially be a mechanical bond. Is a coating being used?

A: Agreed, these are areas of FY21 and future work, FY21 results suggest the bonding is a critical factor

R: It would be very good to see cyclic load testing and impact testing to understand if there are any detrimental interface effects that large plasticity testing does not identify.

A: Agreed, these are areas of FY21 and future work, FY21 results suggest the bonding is a critical factor

FY20 reviewers aggerate



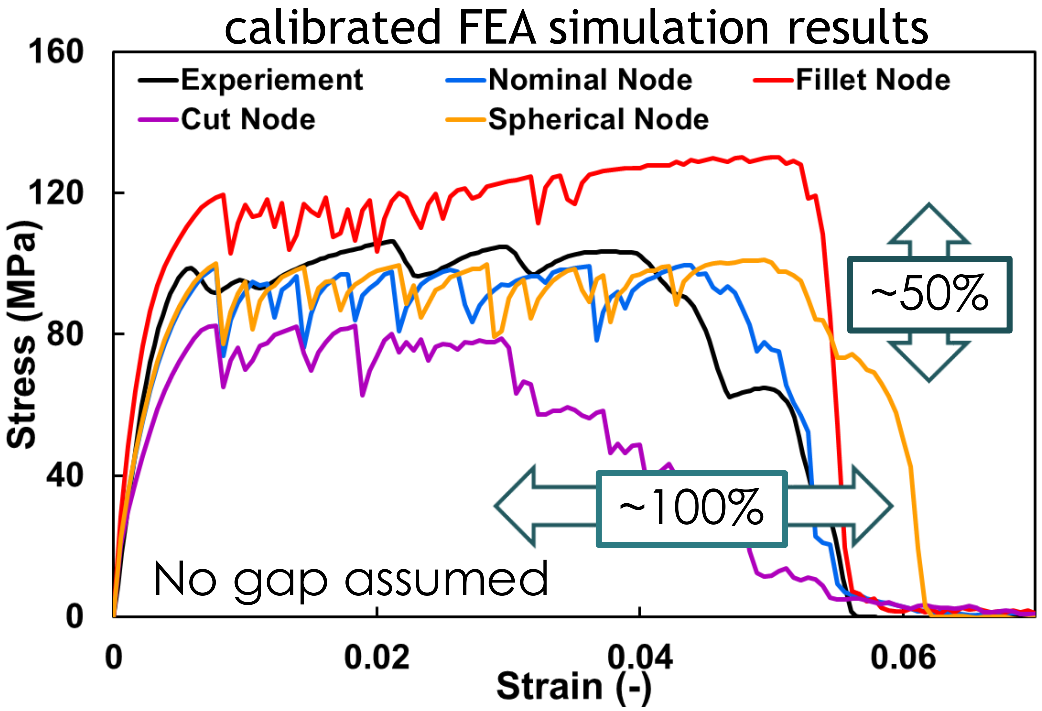
OAK RIDGE National Laboratory

Collaboration and Coordination With Other Institutions

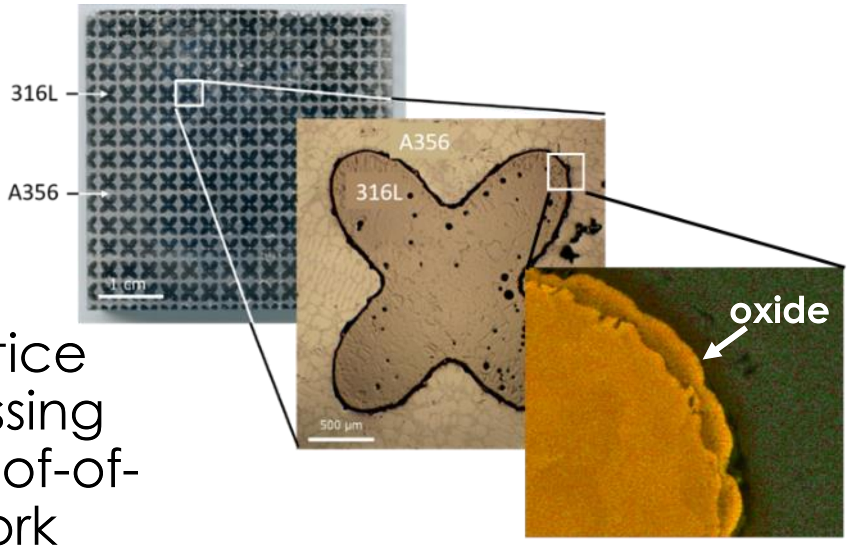
- Rice University/MIT
  - Vacuum casting technique development
- Quintus
  - HIP guidance and physical HIP of samples
- Air Force Research Laboratory
  - Simulation guidance and informal discussions of shock loading approaches
- VTO PCMP Core Task 4 work
  - Microstructure based modeling of interface between constituents and associated bonding effects
- Bechtel
  - Project direction advising and potential for expanded utility
- Internal ORNL collaborations
  - Spallation Neutron Source (SNS)
  - Manufacturing Demonstration Facility (MDF)
  - Advanced characterization Thrust 4A

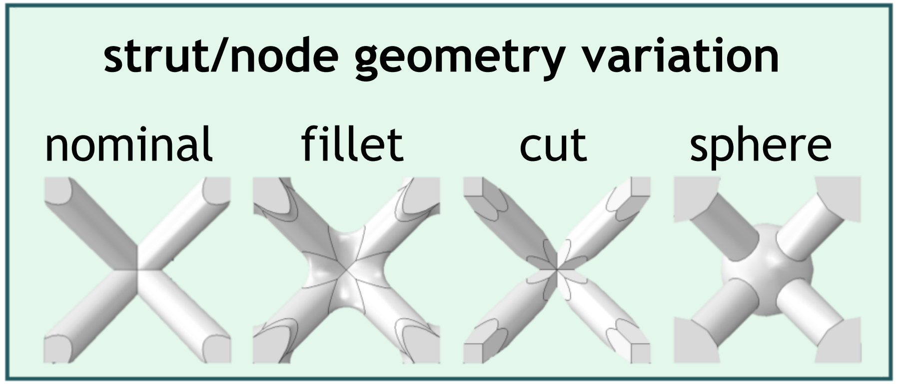
Understanding Lattice Geometry and Interface Effects are Pathways for Reducing Mass and Improving Energy Absorption

- Geometry effects and material opportunities of reinforcement to extend delocalized damage to lower volume fractions (reduced mass)
  - Fillet geometry shows promise in initial simulations
- Interface effects beyond gap remain area for further investigation, processing improvement could be needed



Initial EDS indicates that complex oxides on AM lattice may exist, processing artifacts from proof-of-concept level work





Physical build defects can affect real geometry in this range

Next Steps are evolutionary developments towards full scale demonstration solutions

Any proposed future work is subject to change based on funding levels.

- Potential for local slurries/coating applications to promote or prevent bonding locally enabling fully dense surface with high energy absorption interface and good thermal properties below surface
- New alloy systems of interest for future systems, have started with CF8C+ in collaboration with Task 3B1
- FEA guided design of lattice reinforcement for scale up demonstration
- Fatigue characterization of AMIPC compared to conventional piston alloys

CF8C^{+} AMIPC preforms with fillet geometry

Summary of Work Shows Progress to High Damage Tolerance With Novel Early-Stage Bi-Metallic System

Relevance

- Knock and LSPI are the top barriers to attaining higher efficiency for dilute SI combustion in USDRIVE roadmap, materials that can improve survivability of these events could enable engine efficiency gains

Approach

- A bi-metallic approach combining AM and melt infiltration demonstrates very high damage tolerance
- Approach breaks conventional material tradeoffs and enables new design and efficiency opportunities

Accomplishments

- Observation and mechanical source for transition from localized to delocalized damage determined
- Simulation tool developed to understand physical observations in greater detail and enable optimization
- Role of interface between constituents determined and characterized in measurements and simulations
- Hypervelocity impact results combined with conventional simulation tools developed for impact FEA model
- Piston SPI load simulations underway at relevant conditions, promising opportunity for AMIPC observed

Collaborations

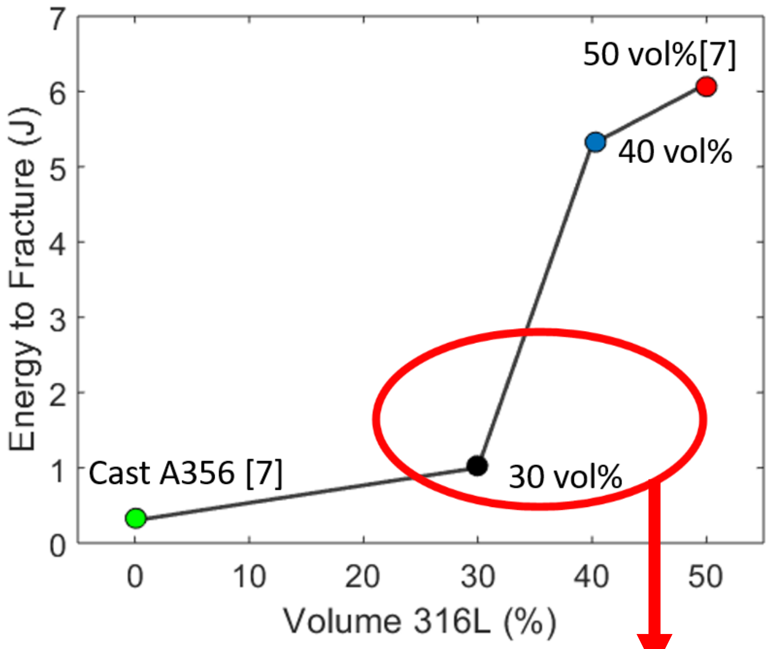
- University, industrial, and defense collaborations have been critical to infiltration technology, simulation approaches, and results discussion towards this program and will continue to be

Future Work

- Future work focuses on lattice geometry effects on shock loading, and scale up to component level problem

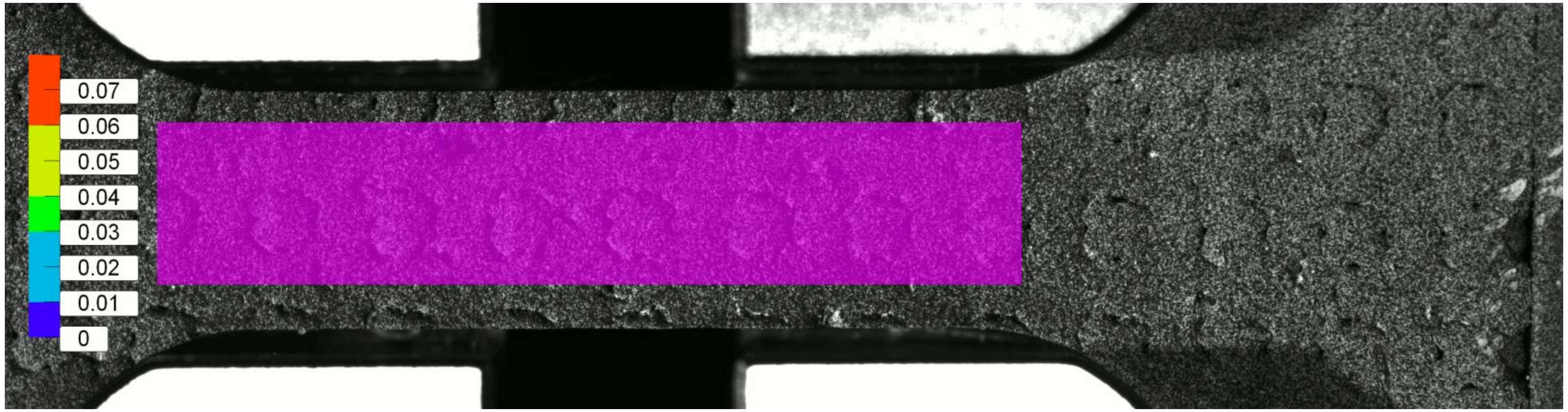
Technical Backup Slide Divider

Transition to Delocalized Damage Enable Dramatic Increase in Energy Absorption

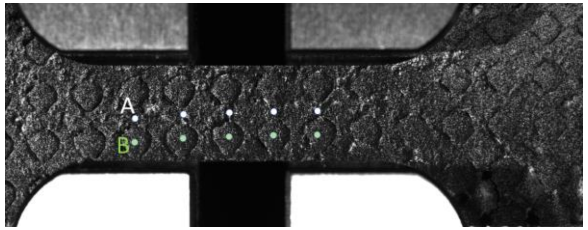


- Measurements show that localized failure occurs in samples with reduced volume fractions
  - DIC measurements highlight that a single crack location occurs and sample fails catastrophically
- Energy to fracture with localized failure is similar to that of aluminum

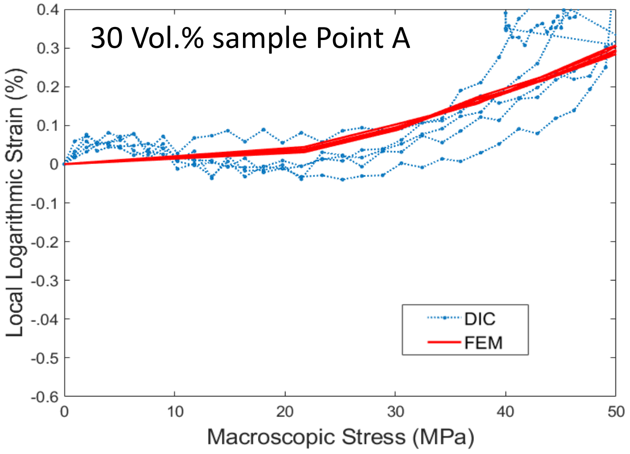
DIC measurement of tensile loading 30% volume fraction 316L SS/A356 BCC

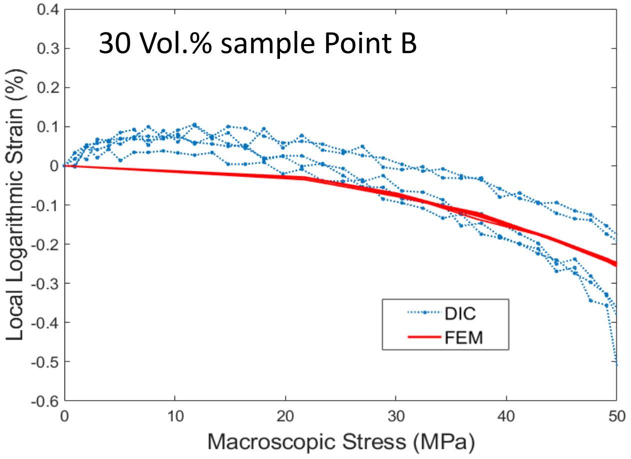


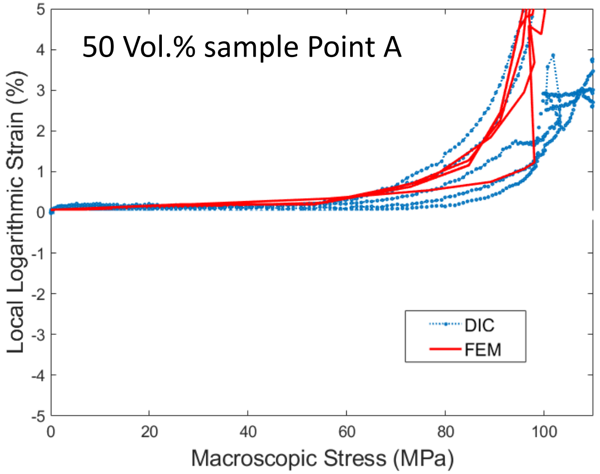
Digital Image Correlation Calibration of FE Model Shows Strong Agreement in Macroscopic Stress/Strain

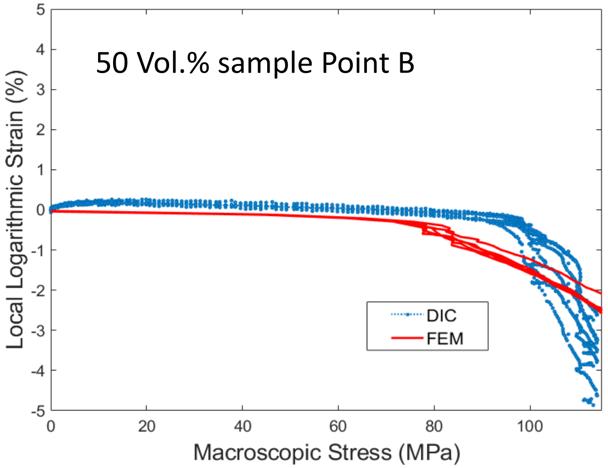


- Multi-location DIC calibration used for FEM tuning
- Good agreement between measurements and FEM predictions
- Tuning applied to FEM for internal geometry inaccessible to Digital Image Correlation





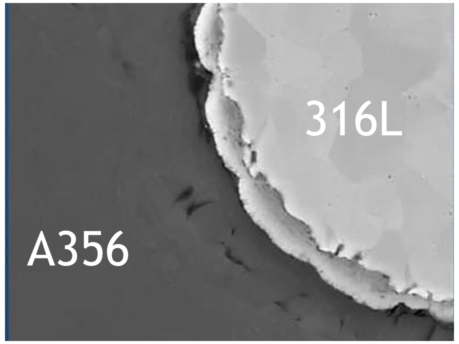


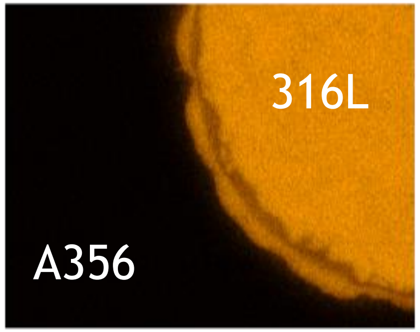


Data from Cheng et al., Materials & Design (2020)

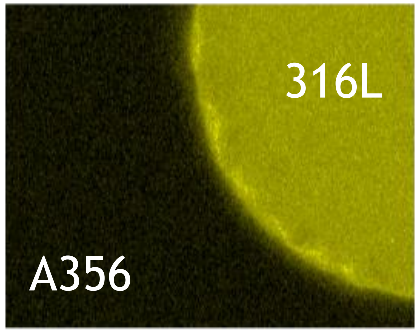
Interface Chemical Analysis shows Oxidation Potential

- Post processing criteria for pre-heat appear to add oxides at interface
- EDS results confirm that boundary effects exist in proof- of-concept level fabrication steps
  - Heated 316L stainless steel in air prior to infiltration shows surface oxidation
- Potential for improved processing control steps and or coatings (e.g. slurries)
  - interface tailorability and selectivity based on simulation and experimental outcomes

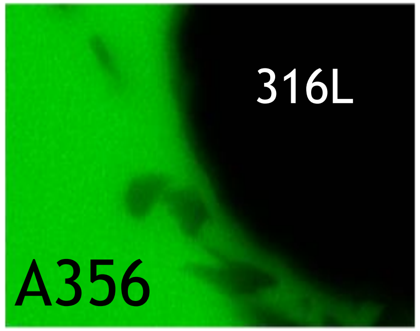




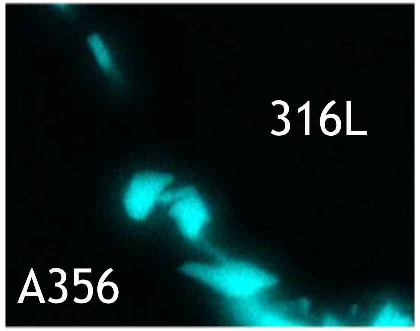
5µm Iron



5µm Chromium



5µm Aluminum



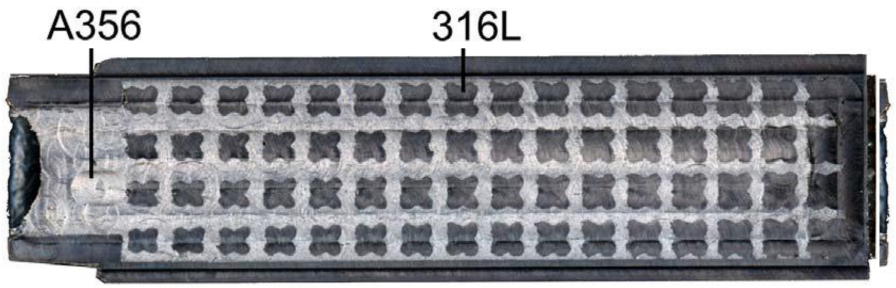
5µm Silicon

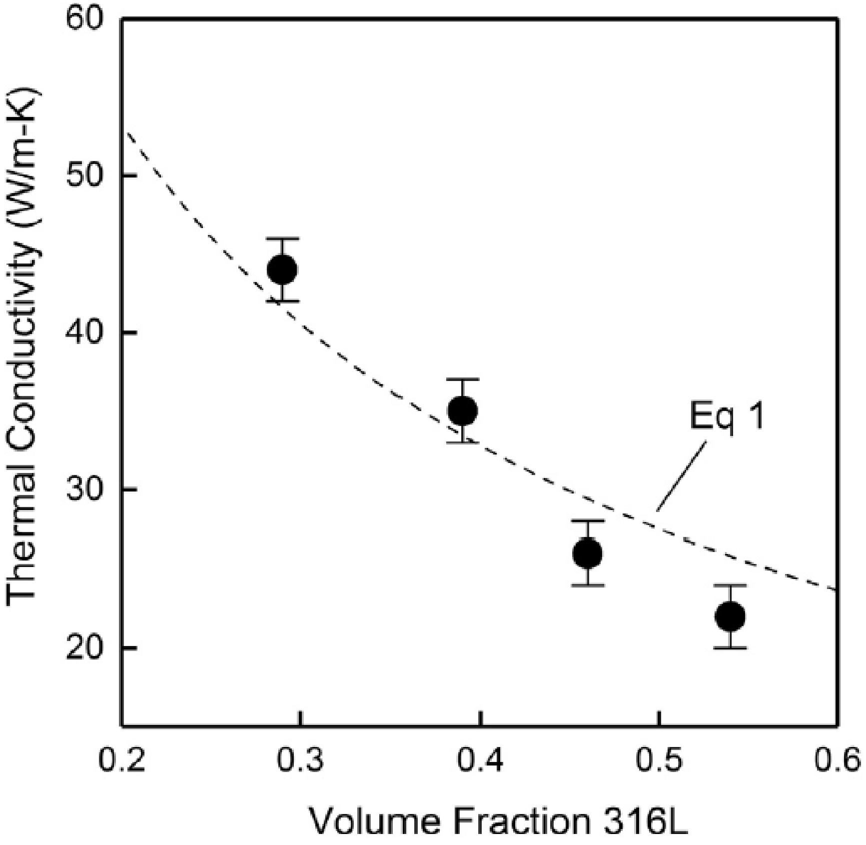
Non-linear thermal conductivity relation with constituents

- Non-linear blending relation of constituents enables optimization potential of thermal-mechanical behaviors

- Functionally graded material or local changes in reinforcement possibility further enhances optimization potential at local level

- Ideal relation for high strength and good thermal conductivity needed in piston top ring zone





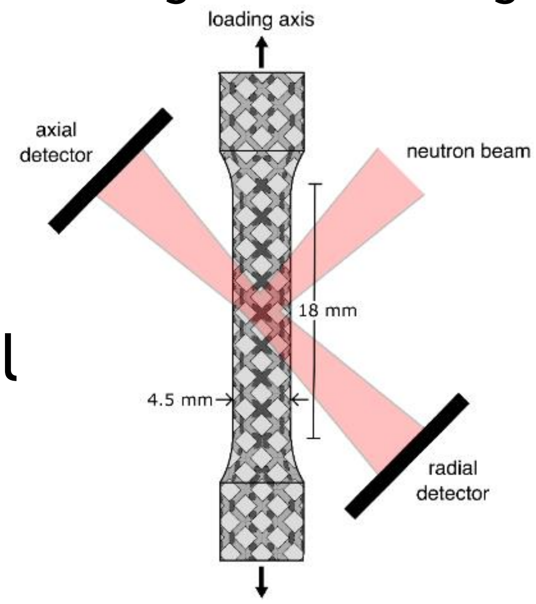
Pawlowski, A.E., et al. *Materials & Design*.

OAK RIDGE
National Laboratory

Neutron Diffraction Reveals "Finger Trap" Type Behavior in Tension, Significantly Increases Damage Tolerance

- In-situ neutron diffraction diagnostics highlight compressive stress state in aluminum reinforcement under tensile loading
  - tensile load only carried by 316L reinforcement
  - Potential to eliminate brittle failure of aluminum in piston ringland area
- Reinforcement alone must not surpass UTS to transition to high damage tolerance
  - Lattice geometry optimization is critical next step

Neutron diffraction during tensile loading



results for different 316L vol. %