Project ID: mat189

2021 DOE Vehicle Technologies Office Annual Merit Review Presentation

Fundamental Development of Aluminum Alloys for Additive Manufacturing*

** Task 3A1 under the Powertrain Materials Core Program (PMCP)*

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Other contributors: Amit Shyam (Co-PI), Ryan Dehoff, Ying Yang, Sumit Bahl, Kevin Sisco, Larry Allard, Richard Michi

Oak Ridge National Laboratory

June 22, 2021

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

PROJECT OVERVIEW

Task 3A1: Fundamental Development of Aluminum Alloys for Additive Manufacturing

Timeline/Budget

- Task start: October 2018
- Task end: September 2023
- Percent complete: 50%
- **3A1 Budget**
  - **FY20: $425k**
  - **FY21: $375K**

Barriers

- New, alloys tailored for additive manufacturing (AM) are needed - very few commercial alloys available for AM
- Cost and scaling barriers for AM
- Little prior work on high temperature lightweight alloys via AM
- Development time. Project leverages an *Integrated computational materials engineering* (ICME) framework to reduce the early & mid-stage development time of new LW alloys by 50%.

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

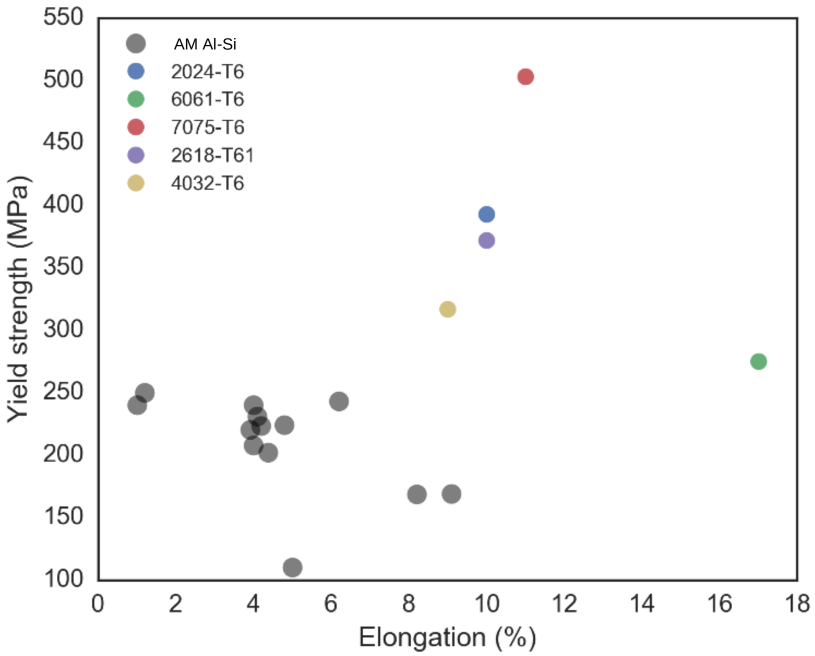
Partners and Collaborators

- Task 3A1 Lead
  - –Oak Ridge National Lab (ORNL)
- Task 3A1 Partners and Collaborators
  - –Eck Industries
  - –Connecticut Engineering Assoc. Corp.
  - –Volunteer Aerospace
  - –University of Tennessee
  - –Northwestern University
  - –University of New South Wales

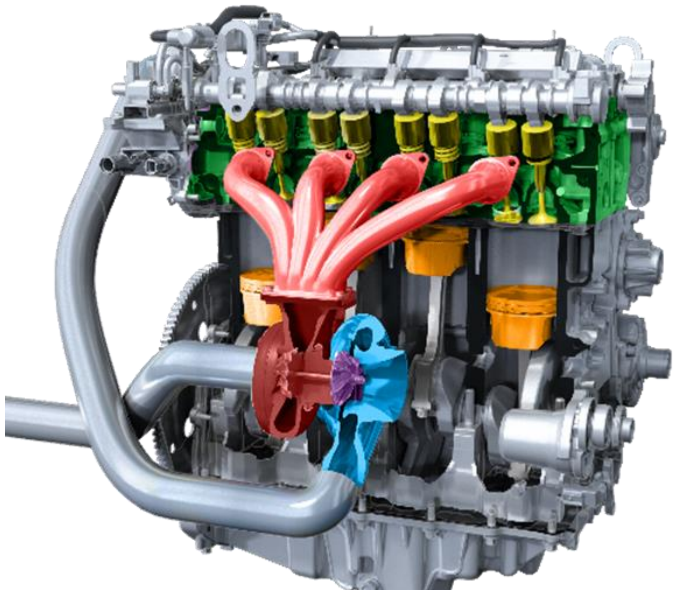
RELEVANCE

Relevance

- Power densities of OEM engines have stagnated as the available lightweight alloys cannot meet the need for high-temperature (250-400°C) performance
- Metal additive manufacturing (AM) offers new design opportunities to improve performance, particularly for lightweight alloys such as Aluminum
  - Strong OEM interest
  - Various applications (pistons, cylinder heads, turbochargers, lightweight brake systems etc.)
- But commercial aluminum alloy selection for AM is limited
  - Hot-tear susceptibility of conventional Al alloys
  - Poor high-temperature property retention
- **Design of new Al alloys for AM has potential to achieve unique microstructures with superior properties to improve engine performance and fuel economy**



Comparison of AM v. wrought properties (see alt-text)



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Milestones

Fundamental Development of LW Alloys for AM

- **FY21 Q1 (3A1): Complete Al-Ce-Ni-Mn creep testing for at least two stress levels each for 300°C and 350°C** **COMPLETE**

- **FY21 Q2 (3A1): Submit a manuscript reviewing high-temperature Al alloy design for additive manufacturing** **COMPLETE**

- **FY21 Q4 (3A1): Submit a manuscript on the microstructure and properties of an additively manufactured Al-Cu-Ce based alloy** **ON TRACK**

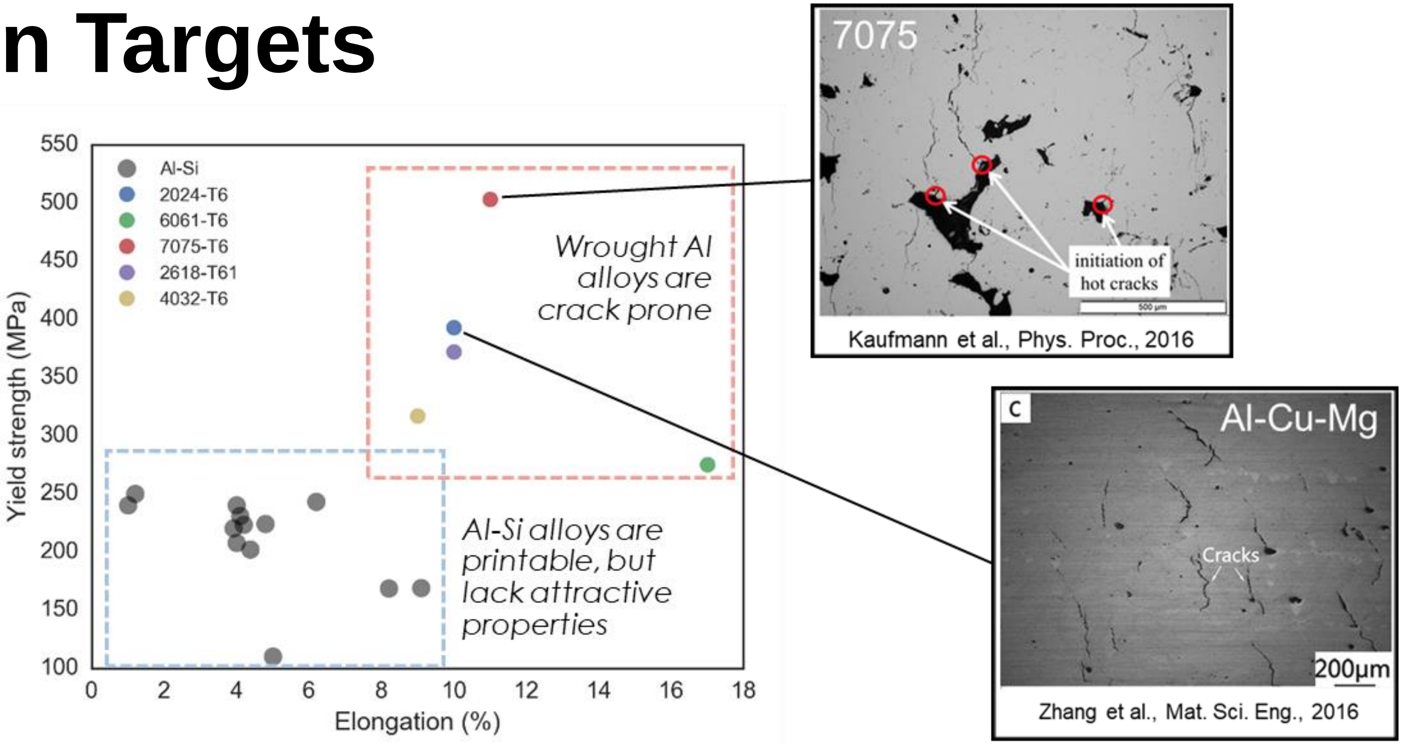
Approach – Alloy Design Targets

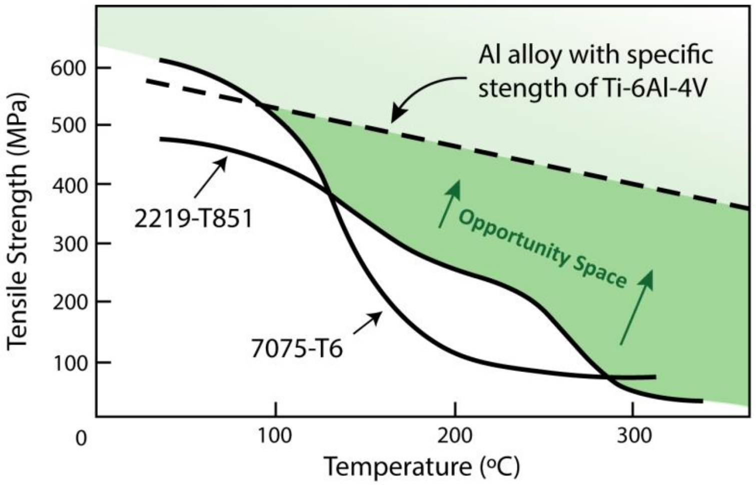
Manufacturing Challenges

- **Solidification cracking** (*i.e.*, hot-tearing)
- **Vaporization loss** of volatile elements
- Increase in material **cost** over Al-Si alloys

Property Requirements

- **High-temperature** mechanical strength
- **Thermally stable** microstructure
- **Creep** and **fatigue** resistance





Hypothesis:

New alloys designed for the **unique processing characteristics of AM** will simultaneously enable **new design concepts** and **improved properties** vs what can be achieved with conventional processing

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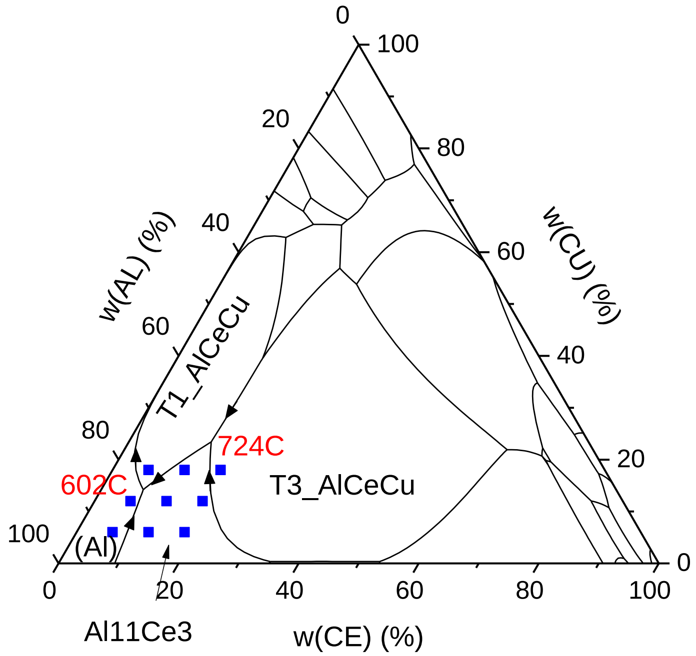
Approach – Alloy Design Strategy



Literature Review

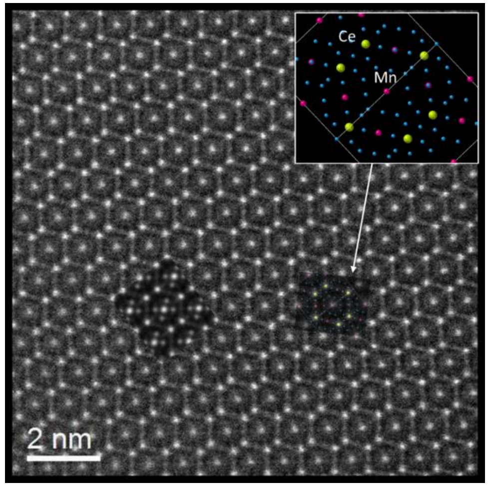
- Learn from casting, welding, and rapid solidification communities
- Apply fundamental materials knowledge

Computational Thermodynamics

- Evaluate hot tearing criteria
- Understand phase evolution

Alloy Selection and Feedstock Production

- Select alloy compositions to maximize information
- Key partnerships for complex powder feedstock production



Rapid Process Optimization

- Understand AM process characteristics
- Optimize process parameters

Testing and Advanced Characterization

- Multiscale characterization
- Property testing

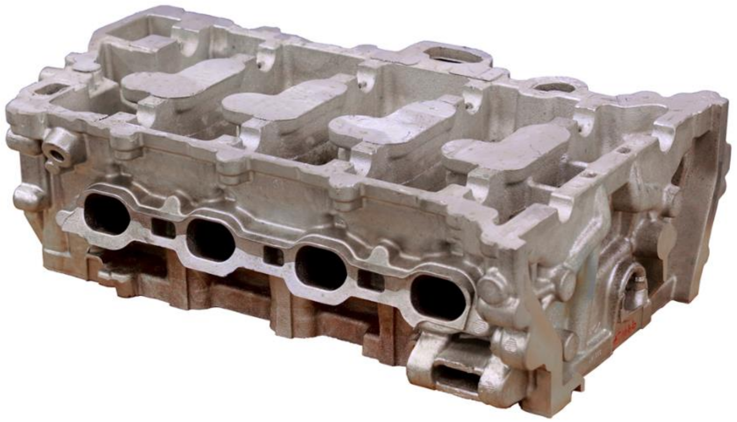
Laser powder bed fusion

Background/introduction

FCA
FIAT CHRYSLER AUTOMOBILES

Nemak

- Previous work, cast alloys
  - ACMZ, Al-Ce
- Previous AMO funded research on AM at the ORNL Manufacturing Demonstration Facility
- PMCP: Bringing together materials and manufacturing expertise
- Selected AM Alloy Systems
  - ACMZ
  - AlCeMn
  - **AlCuCe (Printability, ambient temperature properties)**
  - **AlCeNiMn (High-temperature performance)**
- Related research in Task 3A3 and Thrust 4



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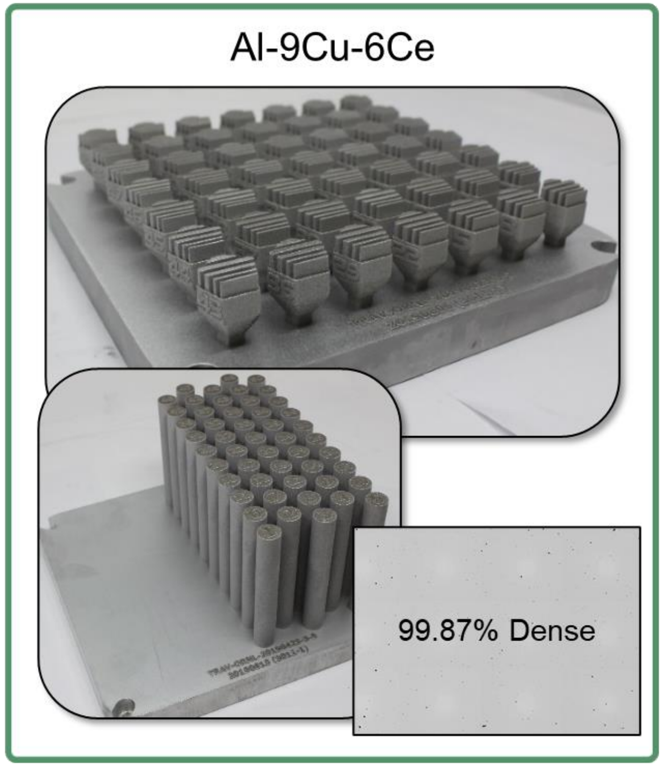
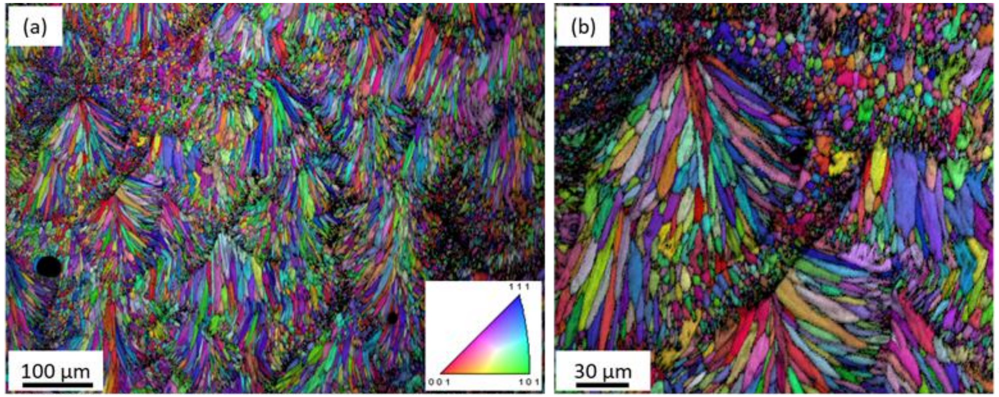
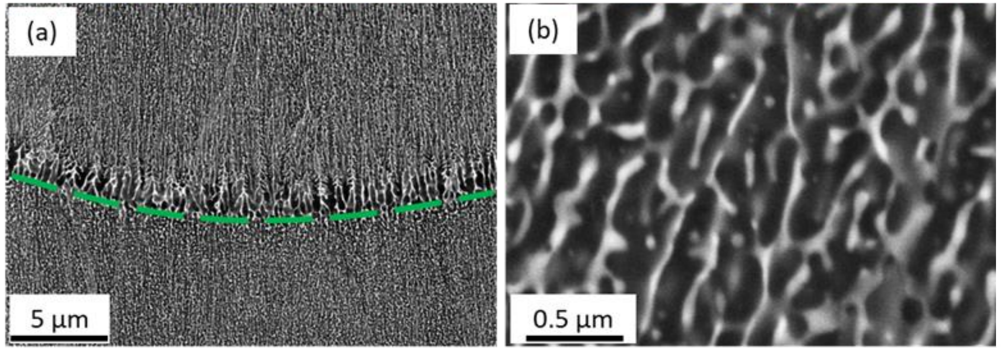
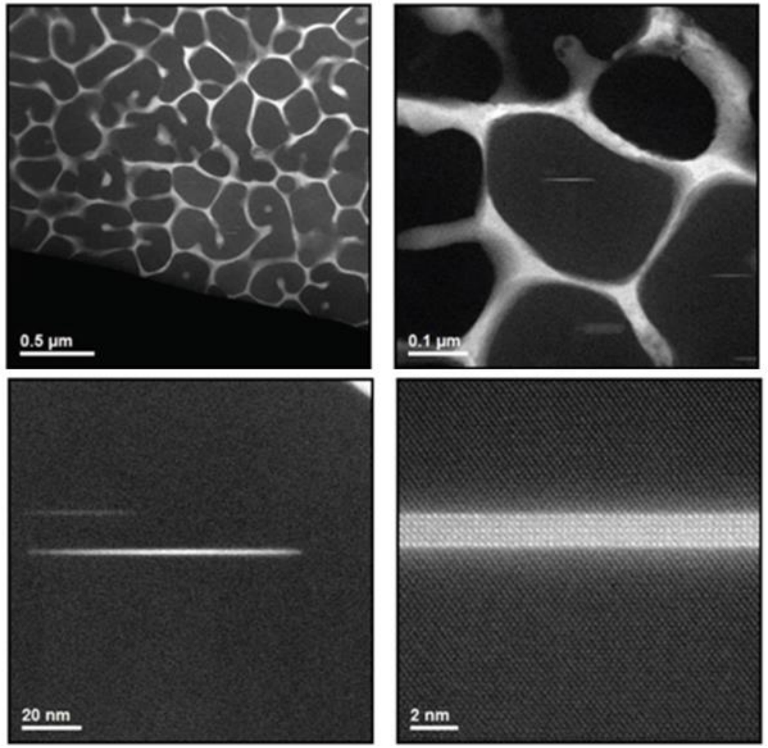
Technical Accomplishments - AlCuCe

- Designed a near-eutectic AlCuCe alloy
- Achieved exception printability across a wide range of process conditions
- Characterization shows a refined grain structure, fine distribution of eutectic intermetallic particles, and in situ formation of θ'



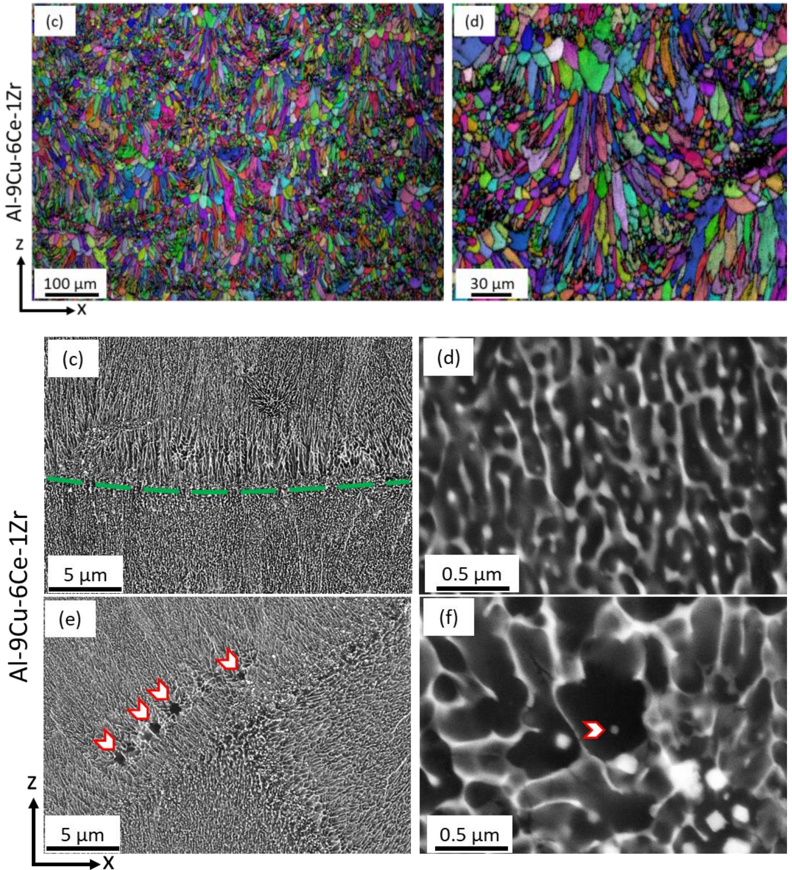


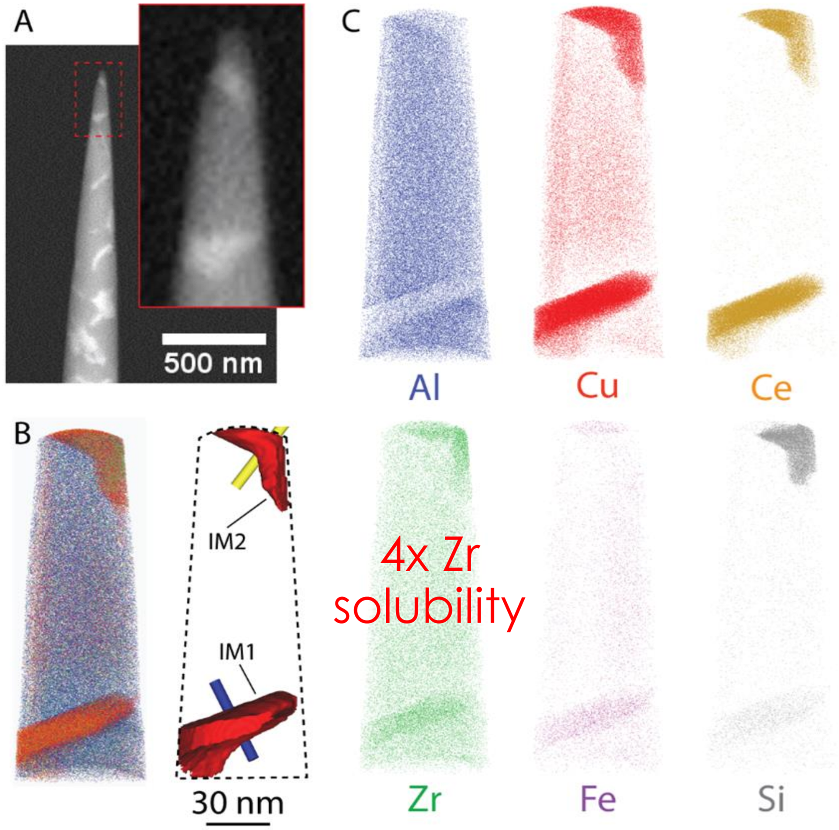




Technical Accomplishments– AlCuCeZr Microstructure

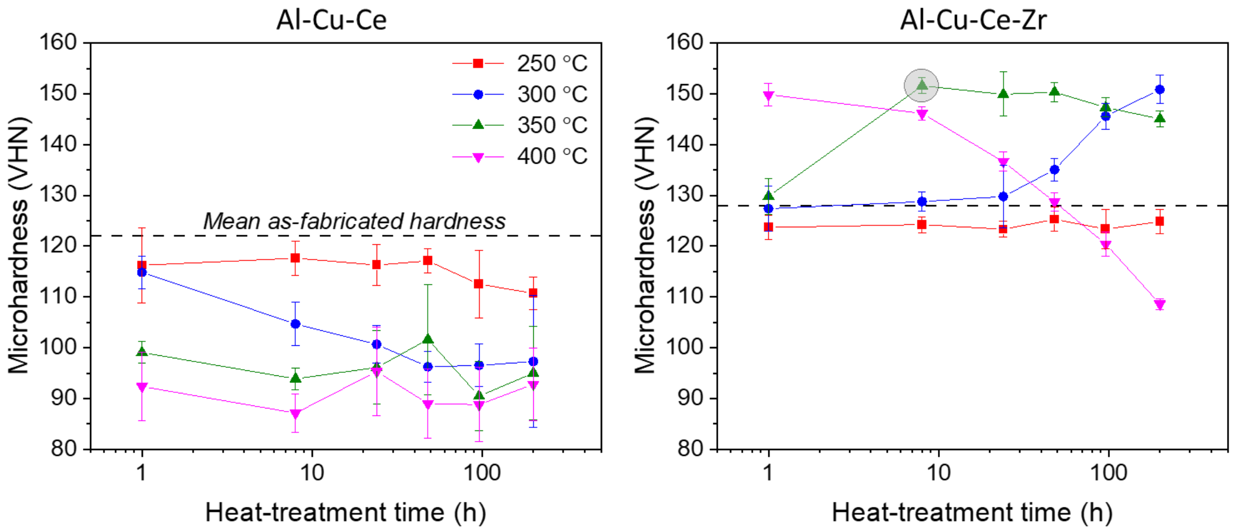
- Exceptional printability across a wide range of process conditions
- Refined grain structure, and fine dispersion of eutectic intermetallic particles
- APT shows Zr within intermetallic particles, but also a super-saturation of Zr in the FCC-Al matrix

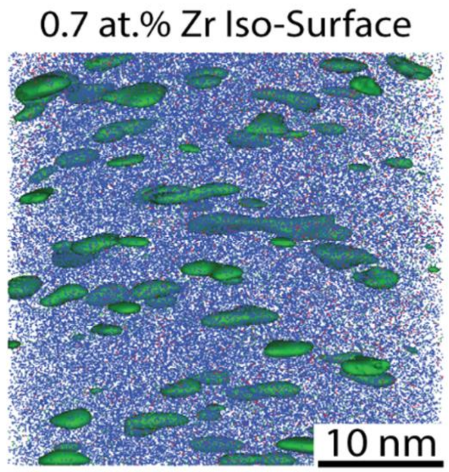




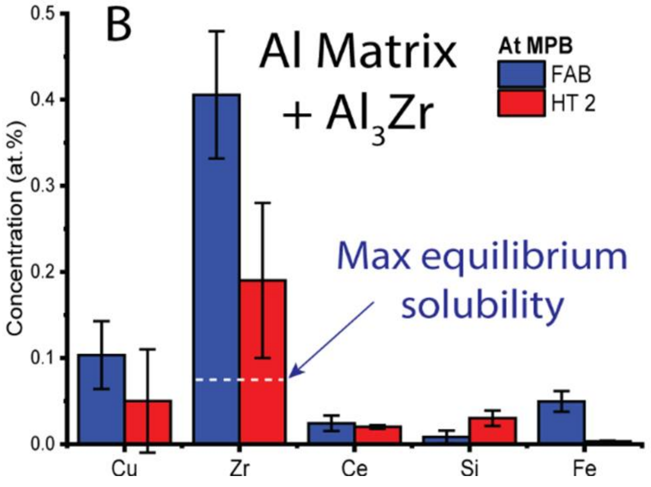
Technical Accomplishments – AlCuCe(Zr) Heat Treatment

- AlCuCe shows high as-fabricated hardness, which decreases due to coarsening at high temperature
- Atom probe tomography (APT) of AlCuCeZr shows significant Zr super-saturation in as-fab state
- Heat treatment of AlCuCeZr leads to significant hardening due to Al_3Zr $L1_2$ precipitation
    - High number density of particles compared to what is possible via casting





Number density



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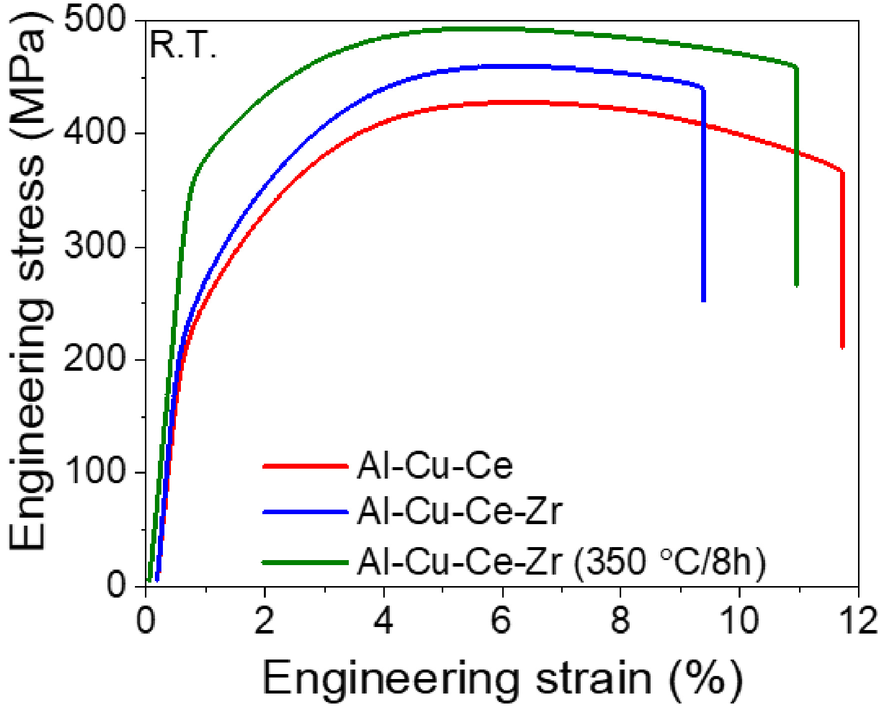
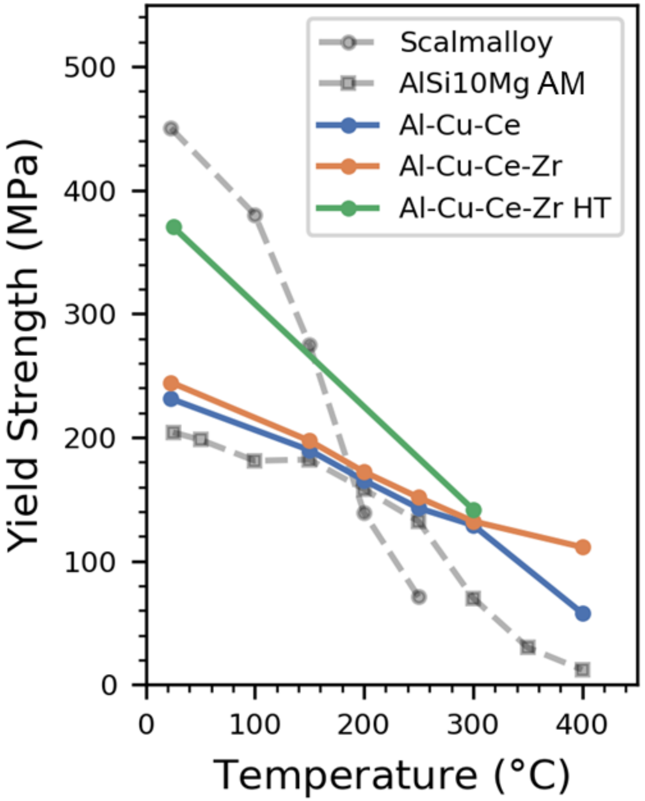
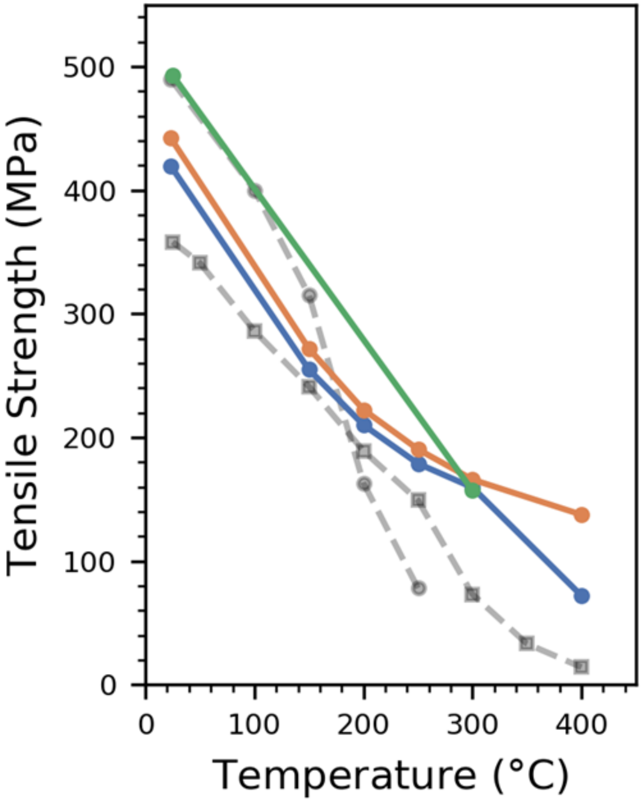
Technical Accomplishments – AlCuCe Mechanical Testing

- High room-temperature strength with good ductility, especially for AlCuCeZr follow heat treatment
- Competitive with Scalmalloy for ambient applications, with better high-temperature strength retention

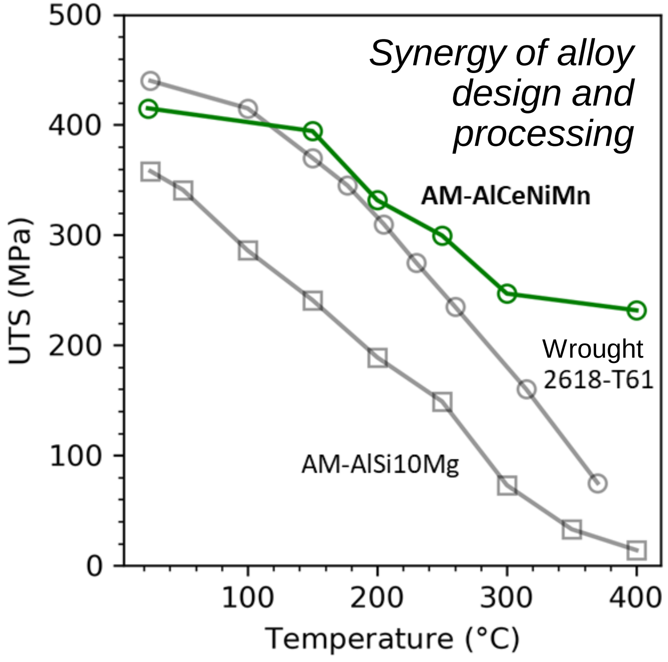






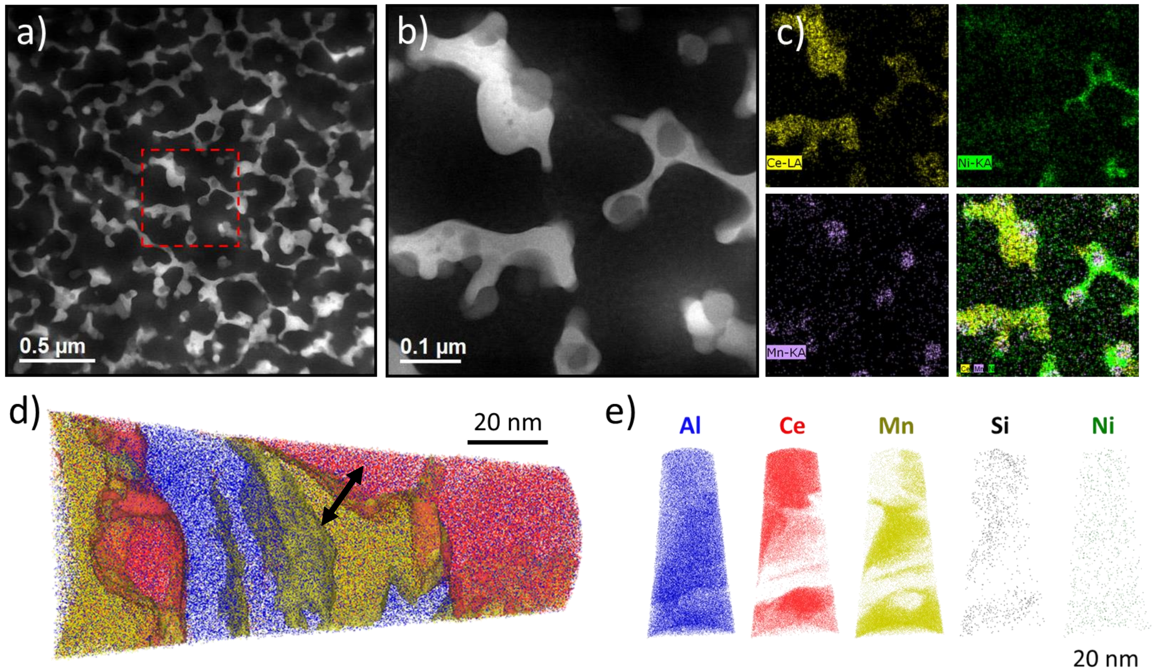
Technical Accomplishments – AlCeNiMn Tensile Data and Microstructure

- Designed a near-eutectic Al-Ce-Ni-Mn alloys for additive manufacturing
- Eutectic compositions reduced hot-tear susceptibility
- High cooling rates in AM refine the solidification microstructure to produce a nano-scale distribution of intermetallic particles
- Exceptional tensile strength as compared to existing AM and wrought alloys



Eutectic microstructure

Atom probe tomography



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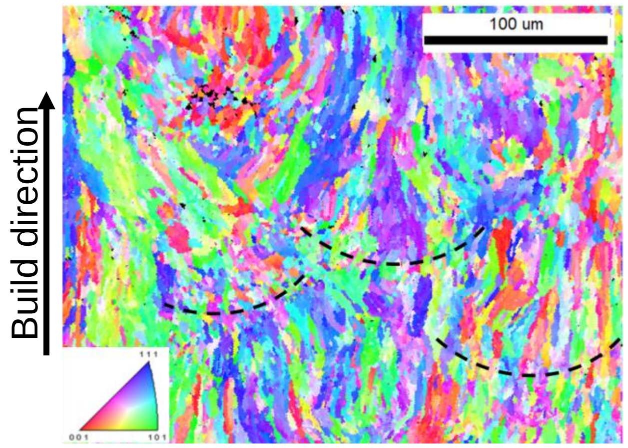
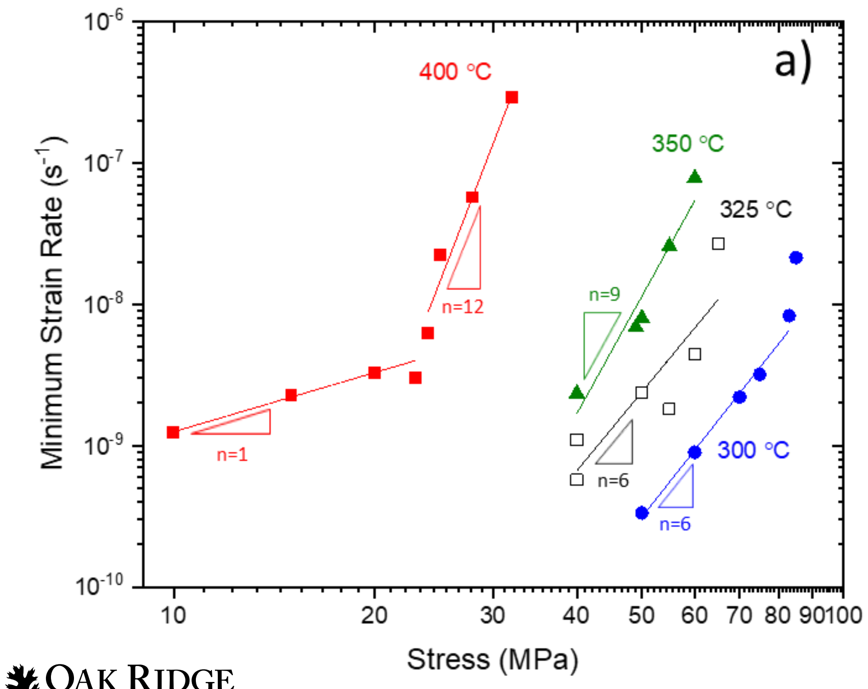
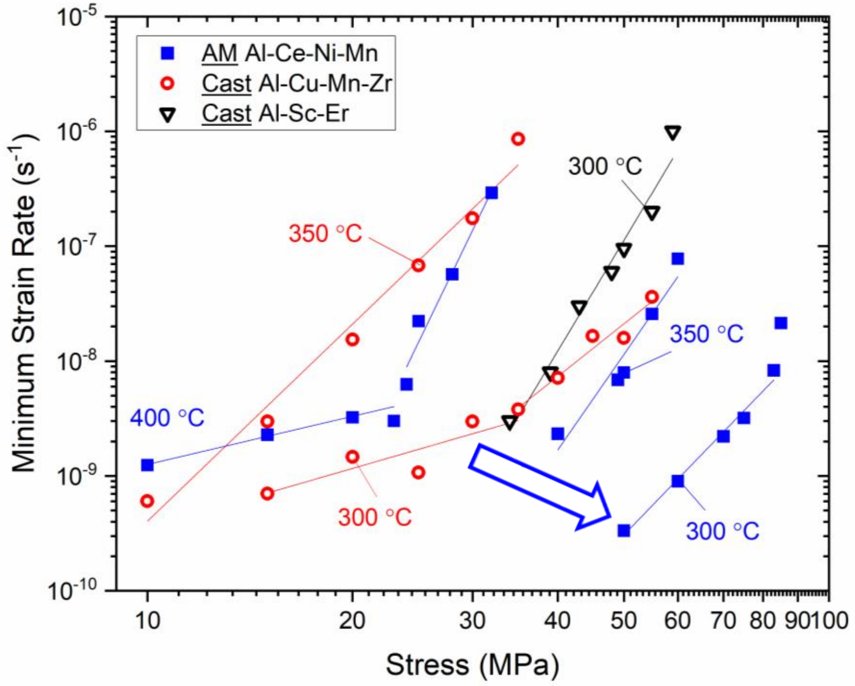
Technical Accomplishments – AlCeNiMn Creep Testing

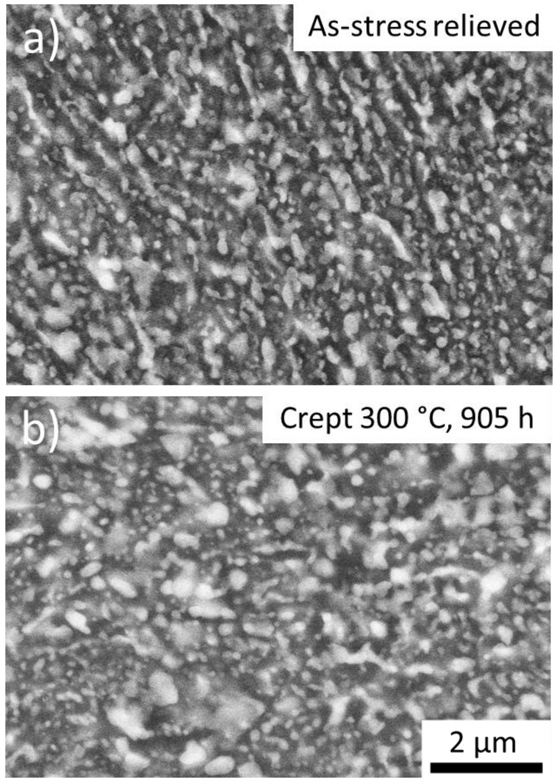
- Initially concerned that small grain size characteristic of AM alloys would lead to poor creep performance
- Creep rates were measured between 300 and 400°C to compare against high-performance cast alloys
- **Lowest measured creep rate for Al alloys at 300°C!**



AM-AlCeNiMn

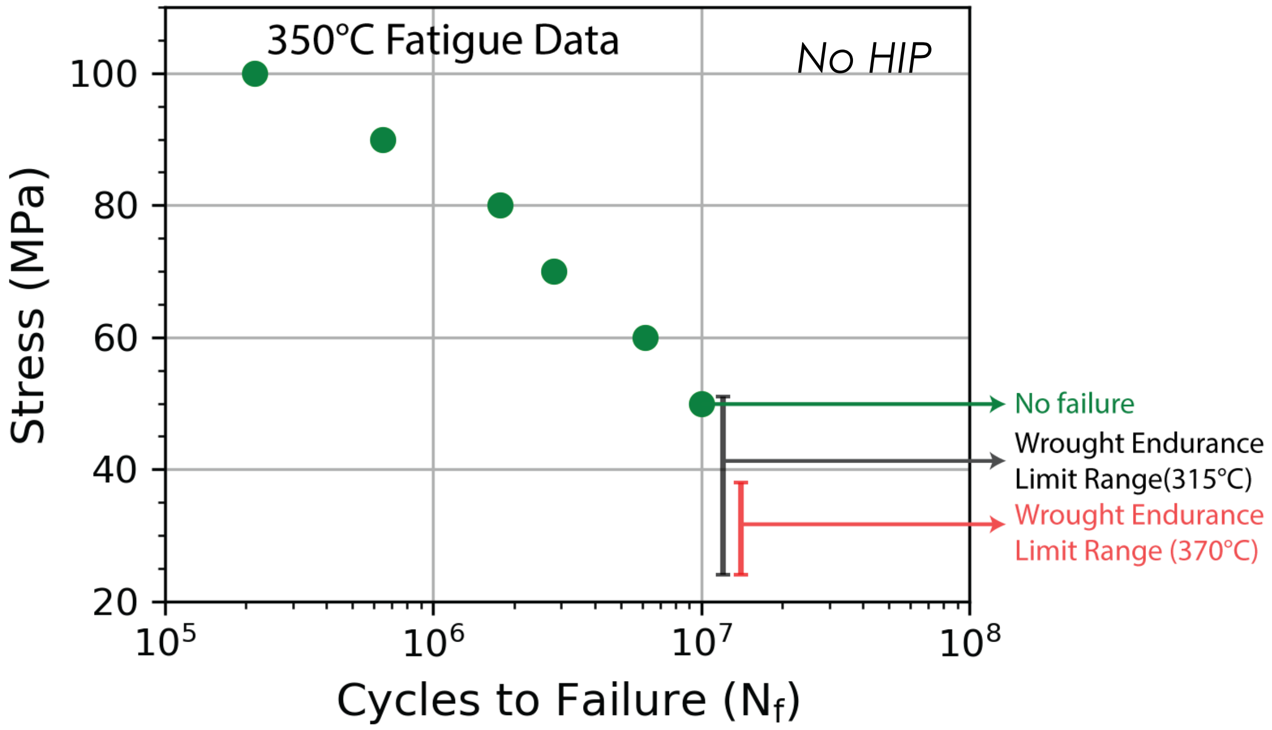






Technical Accomplishments – AlCeNiMn Fatigue

- It is a common concern for AM materials that process defects will limit fatigue performance
- High-cycle fatigue (HCF) was measured for the AM AlCeNiMn alloy at 350°C
- Fatigue limit meets or exceeds wrought alloys in the 315-370°C range
- Fractography underway to understand failure mechanisms
- Incorporation in medium duty truck piston design in CRADA with GM



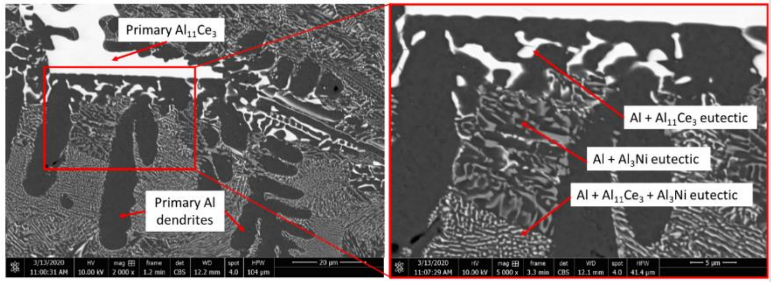
Active CRADA

Collaboration and Coordination

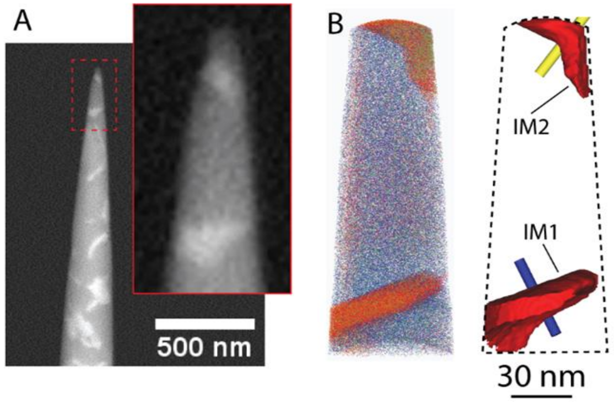
– MDF (AMO), CNMS, ANL

– University of Tennessee – Dr. Suresh Babu
  - Rapid process optimization and characterization

– Northwestern University – Dr. David Dunand
  - Microstructure and creep of AM eutectic Al alloys



– University of New South Wales – Dr. Sophie Primig
  - Advanced characterization of Al-Cu-Ce-Zr



– Thrust 1: Lightweight Alloys – Amit Shyam

– Task 4A: Advanced Characterization – Larry Allard

– Task 3A3: Fundamentals of Non-Equilibrium Processing – Ying Yang

– GM CRADA – Medium duty truck engine light weighting

Remaining Challenges and Barriers

- Non-equilibrium solidification conditions
  - Solidification mode is not consistent with alloy thermodynamics due to high solidification rates and generates **novel microstructures**
    - **Initiated Task 3A3 in FY21 to investigate these questions**
  - Resulting microstructure gives **unique properties** that are not always analogous to cast counterparts, requiring **significant characterization** and expert interpretation
- Lead-time and expense for powder feedstock production
- Bandwidth and lead time for characterization
  - Supported through Thrust 4 and collaborations

FY20 Reviewer Comments

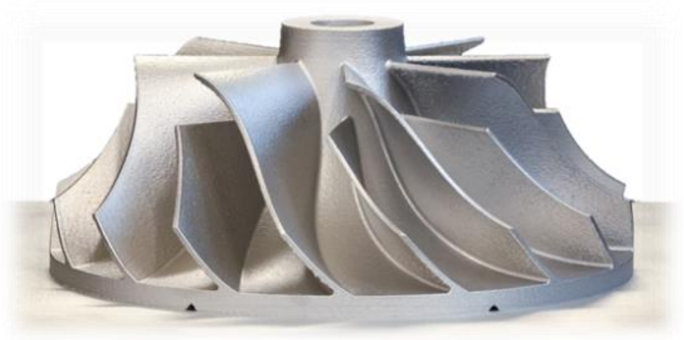
- The project is characterized by a highly structured approach, especially the combination of ICME-based alloy design and experimental work that is executed in a model way. Furthermore, all aspects are put into a **correct technical and industrial background which proves that this work is rather valuable**.

- The reviewer was a bit unclear on the property targets. The reviewer agreed that increased properties are needed at temperatures between 250°C - 400°C, and that AM can be used to print complex geometries (not possible in castings), but **did not see what the targets (yield, ultimate, elongation) are**, and at what temperatures.
  - Property targets are being driven by specific applications and industrial partners. For example, our collaboration with GM has driven our fatigue testing procedures and targets. Results are benchmarked against current state-of-the-art for a given applications

- A point that has not been considered so far is an **analysis of the fatigue properties** of the newly developed alloys.
  - Fatigue and creep testing has been performed for FY21, with additional testing planned for the future to meet specific application requirement

Proposed Future Research

- FY21
  - Complete alloy testing and characterization
  - Publications
- FY22 and beyond
  - Alloy characterization to understand non-equilibrium microstructure evolution in response to AM processing
  - Codifying design rules for printability and high-temperature properties
  - Prototype components for powertrain applications
    - Pistons, cylinder heads, turbocharger components



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

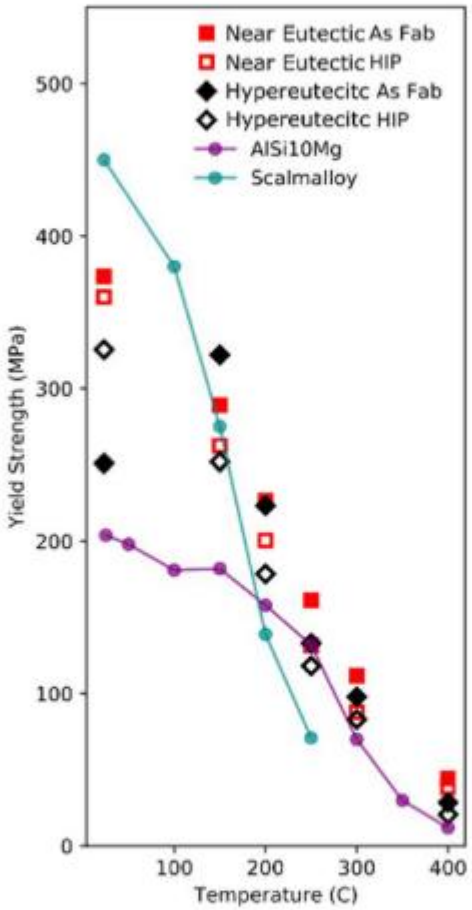
Summary

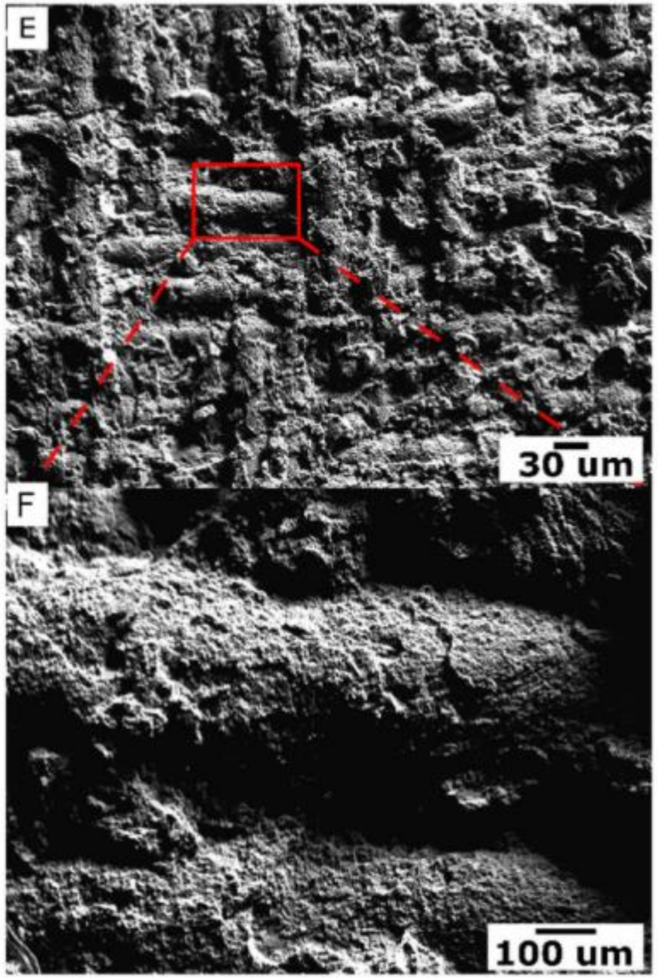
- Approach
  - Design new Al alloys for additive manufacturing to produce unique microstructures and superior property combinations
  - Targeting design toward resistance to hot-tearing and good high-temperature mechanical properties
- Technical Accomplishments
  - Demonstrated excellent high-temperature strength, creep, and fatigue performance of an AM AlCeNiMn alloy
  - Designed and characterized hot-tear resistant AlCuCe alloy, including the use of Zr for precipitation hardening
- Collaborators
  - University of Tennessee, Northwestern University, University of New South Wales
- Future Work
  - Alloy testing and characterization
  - Publications
  - Integration with industrial collaborations

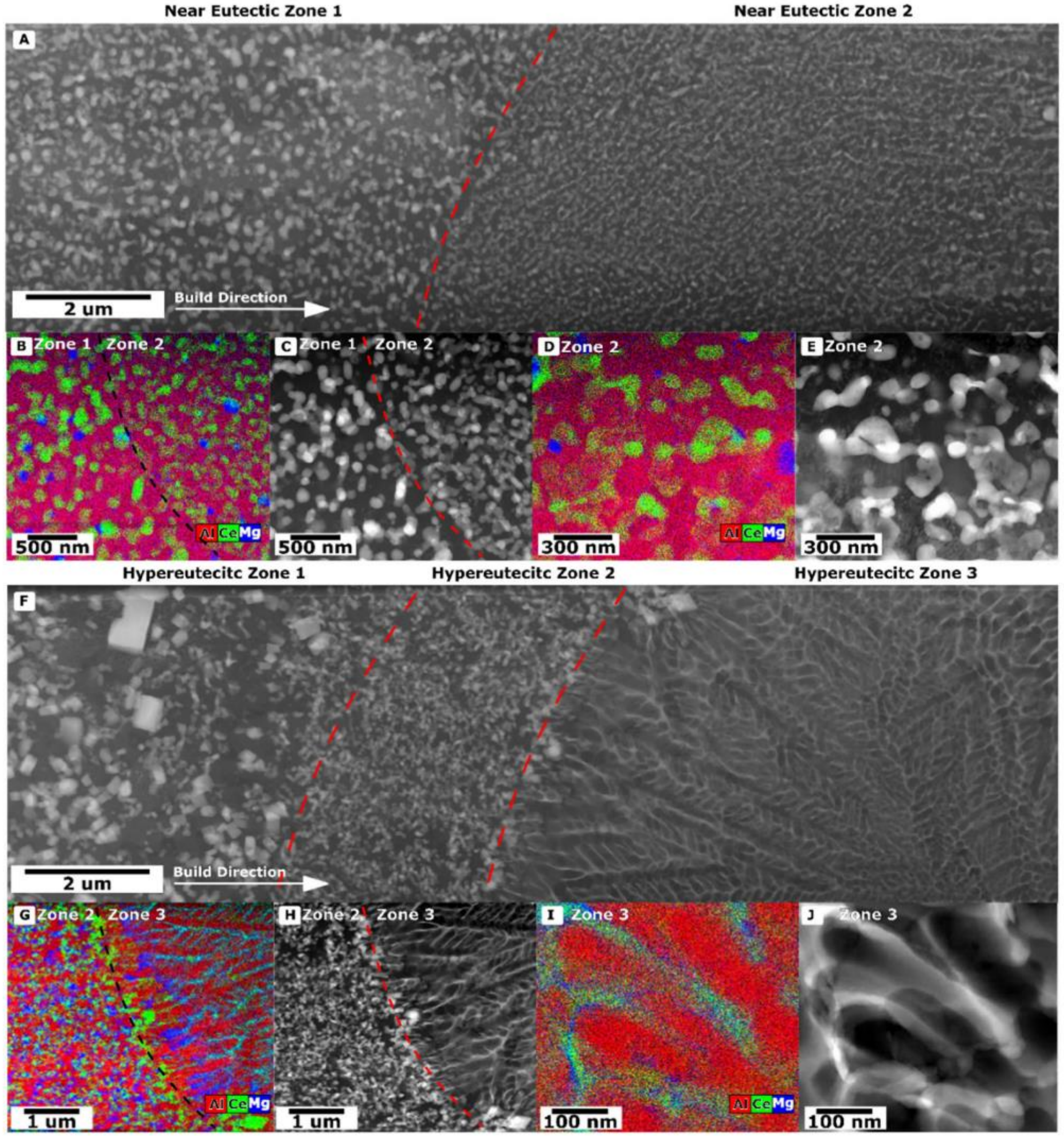
Technical Back-Up Divider Slide

Technical Back-Up: FY21 Results – Published Paper on Microstructure and Properties in AM AlCeMg Alloys

- Published in Scientific Reports

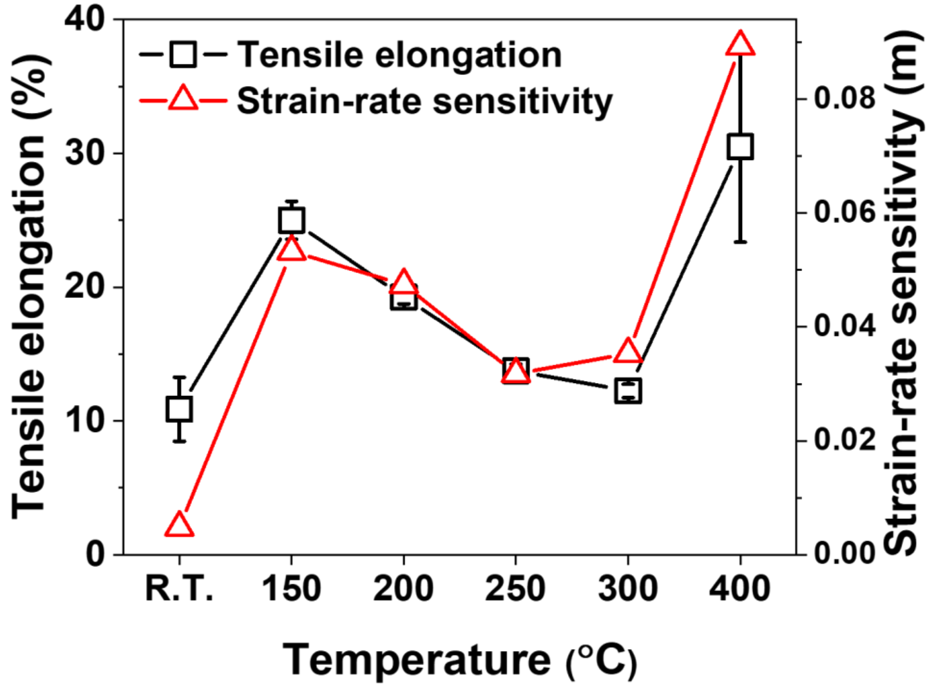


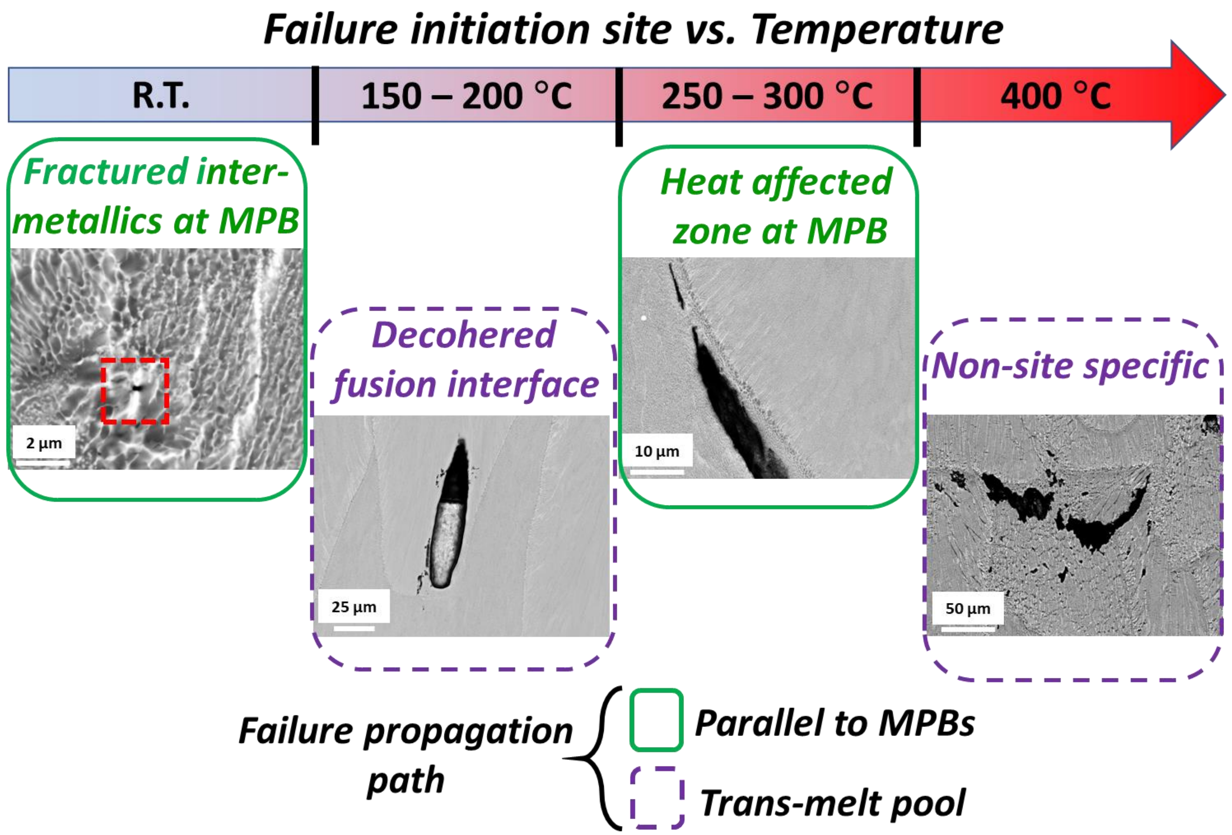




Technical Back-Up: FY21 Results – Submitted Paper on Fracture Modes in AlCuCe as a Function of Temperature

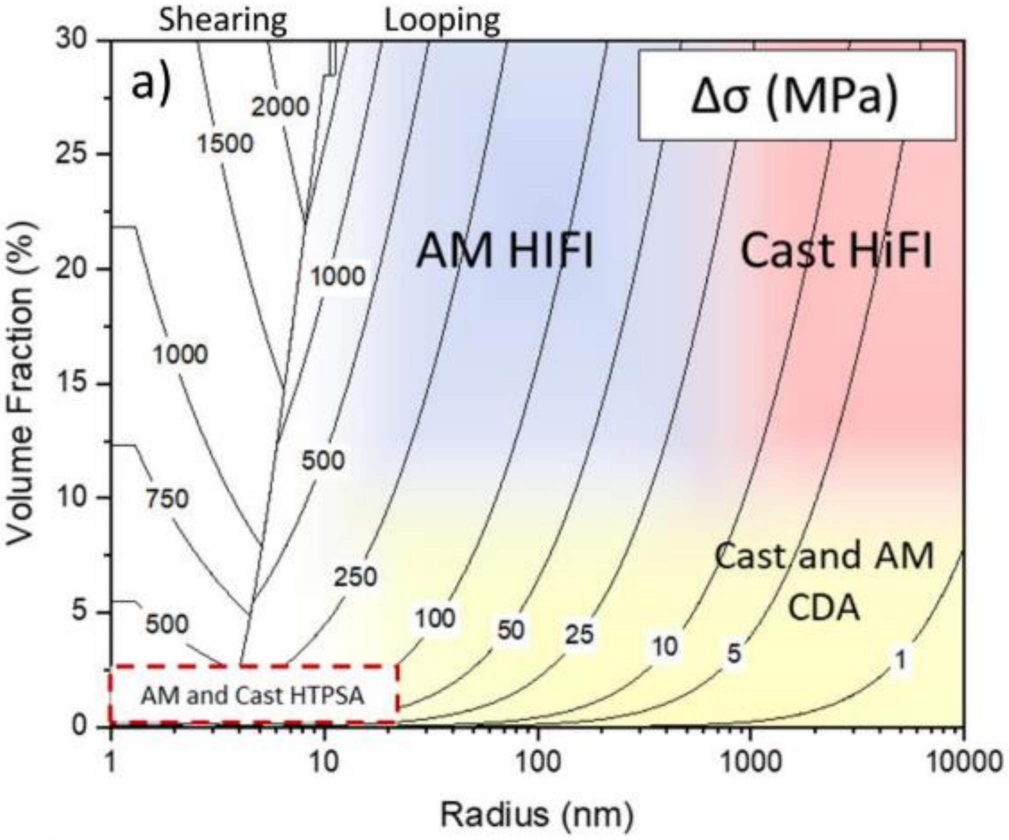
- In review at Acta Materialia



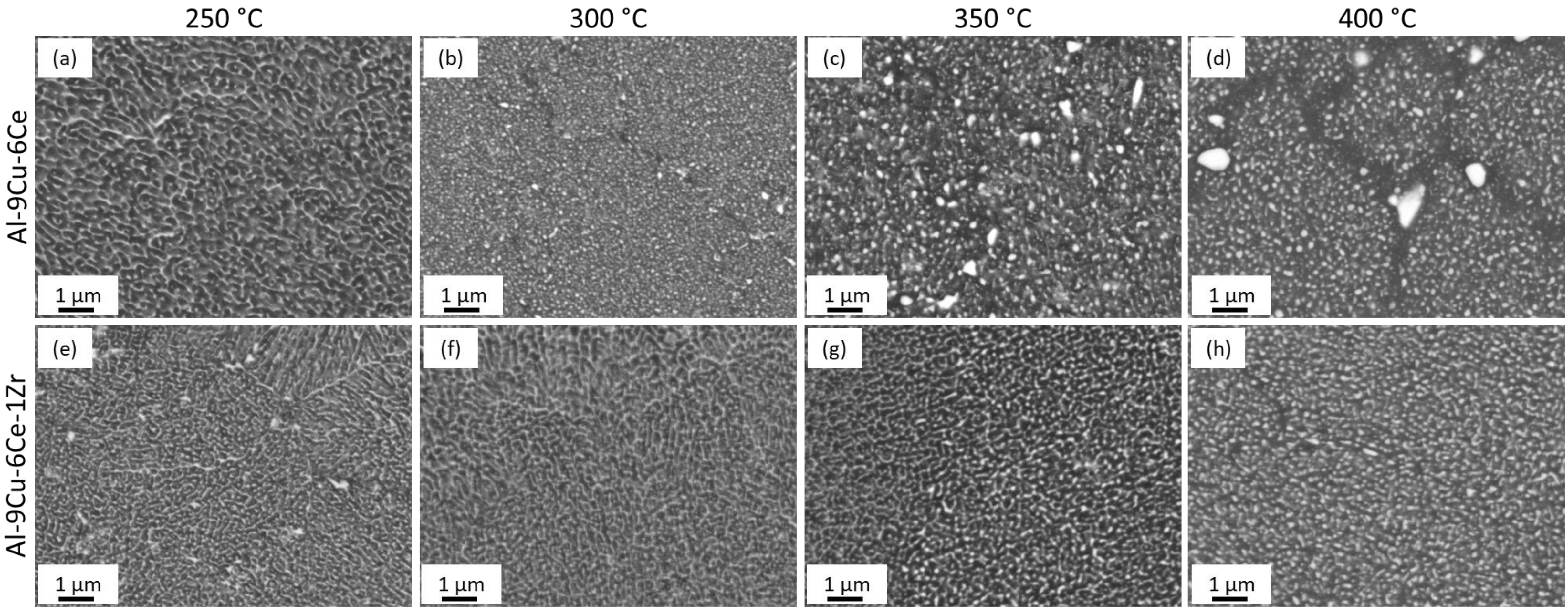


Technical Back-Up: FY21 Results – Submitted Review Article AM Enabled High-Temperature Al Alloys

- In review at International Materials Reviews



Technical Accomplishments and Progress – AlCuCe(Zr) Coarsening



Micrographs shown following thermal 200 hour thermal exposure at each temperature