OAK RIDGE National Laboratory

Project ID: mat220

Ferritic Alloys for Heavy-Duty Pistons via Additive Manufacturing

Task 3B2 under the Powertrain Materials Core Program (PMCP)

Peeyush Nandwana (PI), Rangasayee Kannan, Sebastien Dryepondt, Dean Pierce, Christopher Fancher, Kinga Unocic, Ryan Dehoff, ORNL

Arun Devaraj, Dalong Zhang, Jia Liu, PNNL

2021 DOE Vehicle Technologies Office Annual Merit Review

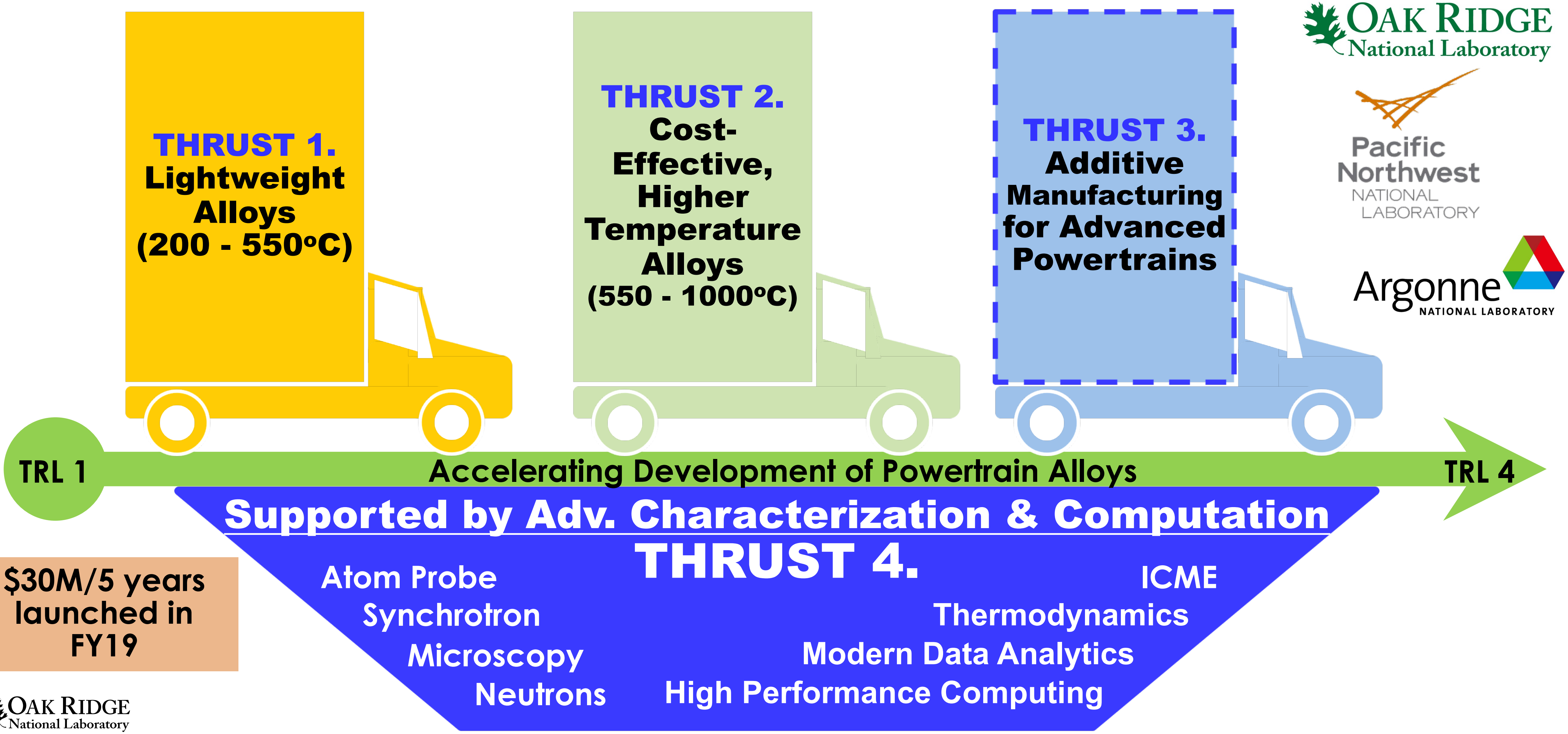
June 23, 2021

PROGRAM OVERVIEW

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

$30M/5 years launched in FY19

Project Overview: Task3B2: Ferritic Alloys for HD Pistons via Additive Manufacturing

Timeline/Budget

- Project start: Oct 2018
- Project end: Sep 2022
- Percent complete: 50%
- **3B2 Budget**
  - **FY20: $225k**
  - **FY21: $225K**

Barriers

- Densification without distortion
- Changing geometries require multiple iterations
- Process control and impact on subsequent microstructure evolution and post-processing
- Representative thermo-kinetic models to capture the phase evolution during the entire sintering and post-heat treatment

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 Lead Lab
  - Oak Ridge National Lab (ORNL)
- Partners
  - Thrust 4A
    - Pacific Northwest National Lab (PNNL)
      - Environmental Molecular Sciences Laboratory (EMSL)
  - Thrust 4B
    - Oak Ridge National Lab (ORNL)

Relevance: Binder Jet AM for High Volume Powertrain Applications

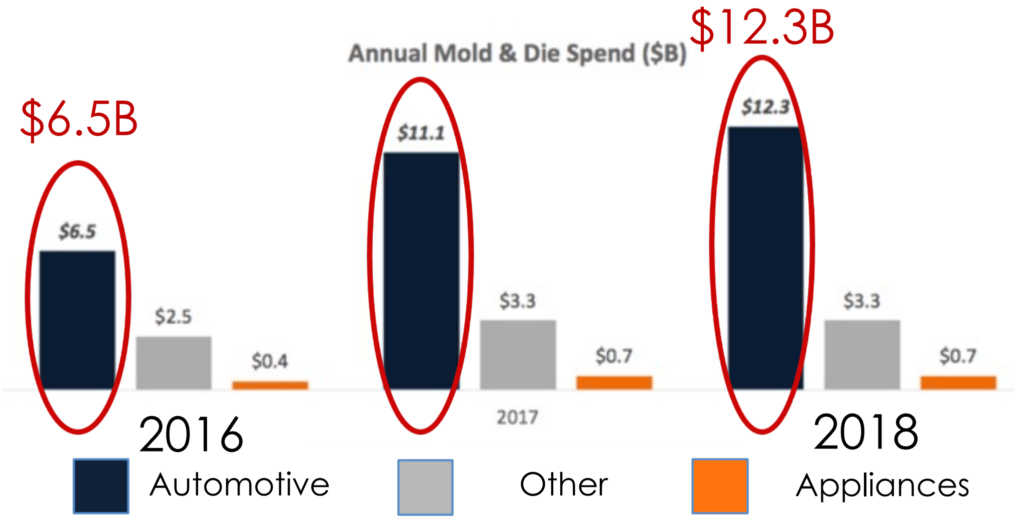
Current heavy-duty engines have low fuel efficiency of ~6-7mpg[1]

Binder jet AM a versatile solution for automotive sector:

- **<u>Powertrain materials</u>**
    - Pistons for heavy duty (HD) engines for line haul <u>freight</u> for <u>improved efficiency</u>
    - Line haul freight sector most difficult to electrify & expected to double by 2040
    - Binder jet enables effective cooling channels, eliminates welds, near net shaping allowing use of difficult to machine materials, advanced materials
    - Binder jet is high volume & low cost compared to other AM processes

MPIF

- **<u>Tooling</u>**
    - Binder jet can enable low cost tooling for automotive
    - AM tool designs for improved efficiency & delivery rate
    - <u>Relevant as the transportation sector undergoes electrification</u>



Oak Ridge National Laboratory

1. Pierce et al. Progress in Materials Science, 2019

Milestones for Task 3B2

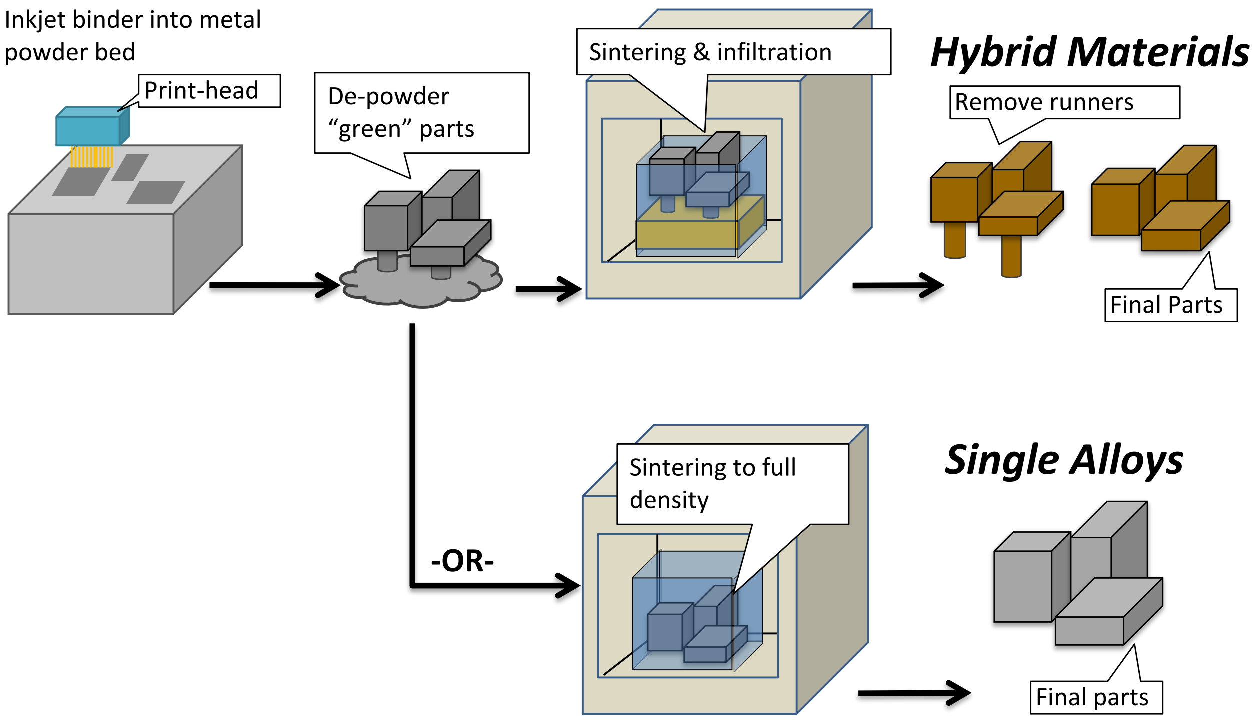
Q1: Conduct tensile testing on binder jet printed H13 steel samples subjected to long term exposure to elevated temperatures. As an example, 550C for 500 hrs. These samples will be post-processed using the conventional heat treatments for alloy H13.
Complete

Q2: Heat treatment optimization of printed H13 based on CALPHAD calculations to improve the properties obtained in Q1, followed by measurement of the material's mechanical properties.
Anticipated Completion in Q3

Q3: Initiate thermodynamic modeling for understanding spatio-temporal evolution of carbides binder jetted steels in as-sintered and heat-treated conditions (solutionized and aged).
On Track

Q4: Submit a paper on correlation between room and high temperature tensile properties and microstructure evolution of binder jet printed H13 steels followed by hot isostatic pressing, and solutionizing and aging
On Track

Introduction to binder jet process & steels of interest

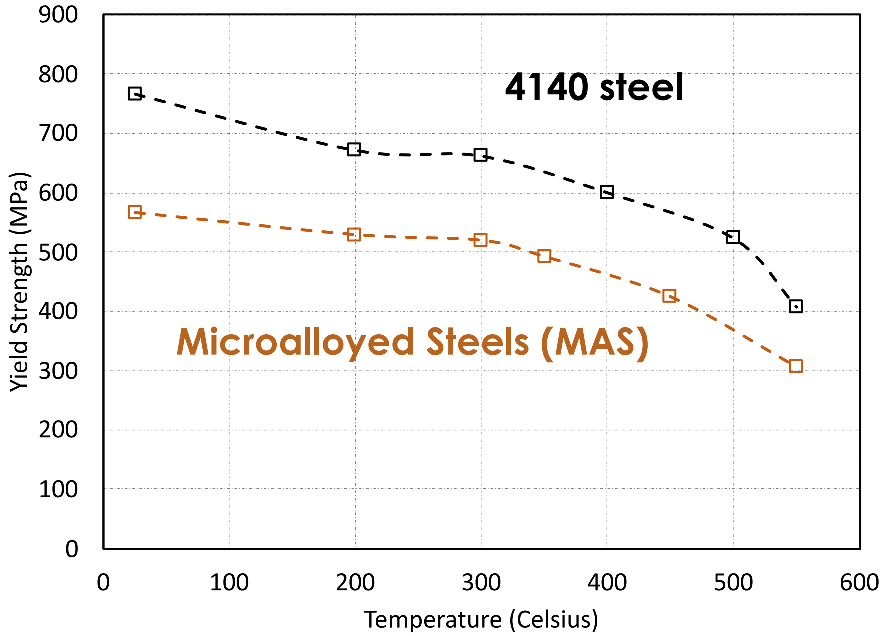


Binder Jet:

- Printing: amount of binder (saturation), dry time, layer thickness, layer time, powder bed density
- Binder burnout and sintering: elevated temperatures to increase density
- Hot isostatic pressing (HIP): high temperature high pressure treatment to mitigate residual porosity

Current Baseline Piston Materials:

Alloy 4140 & Microalloyed steels (MAS) due to low cost and high machinability



Can H13 be potential piston material?

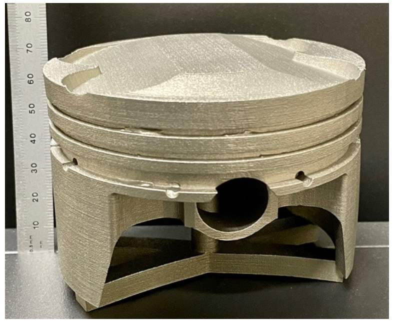
- Poor machinability of H13 can be mitigated by near net shaping in binder jet
- Improved oxidation resistance: Higher Cr (5%) in H13 compared to 4140 (1%)
- Property targets: Exceed the YS of 4140 and MAS steels
- Sinterability demonstrated[1] and is readily available as powder feedstock

1. *Nandwana et al. Additive Manufacturing, 2020*

Rapid Fabrication enabled by AM and Characterization Guided by ICME

Fabrication → Sintering & Densification → Materials Characterization ↔ ICME Approach for Heat Treatment Optimization

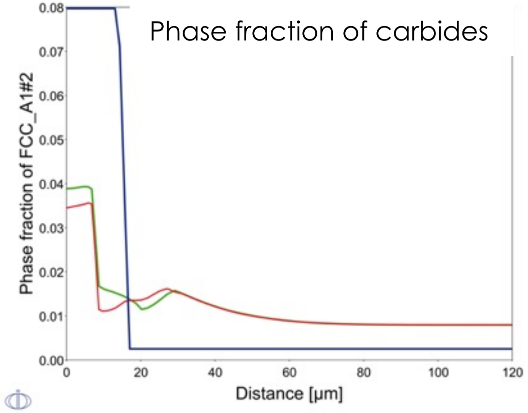
Binder Jet AM



Advanced furnace capabilities with in-situ monitoring

AMO+VTO Collaboration for furnace procurement

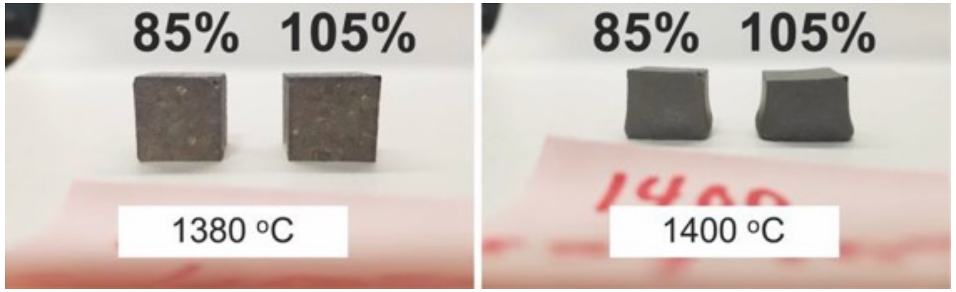
Advanced Characterization



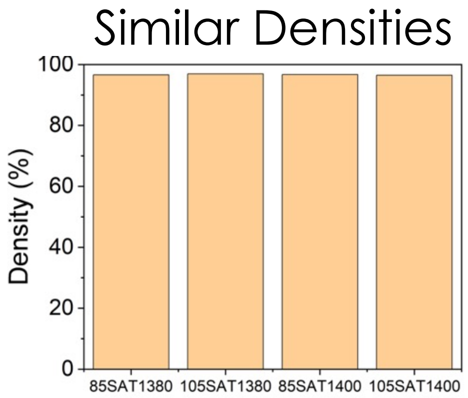
Thermo-kinetic calculations

Balancing between Densification & Distortion in H13

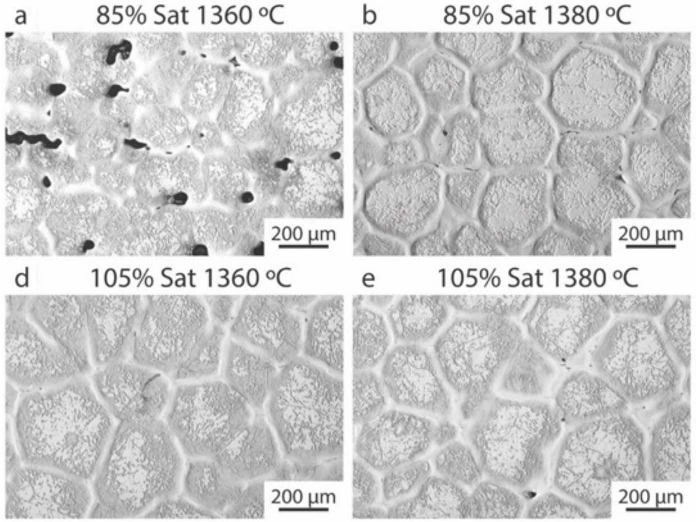
Sintering and Shape Loss

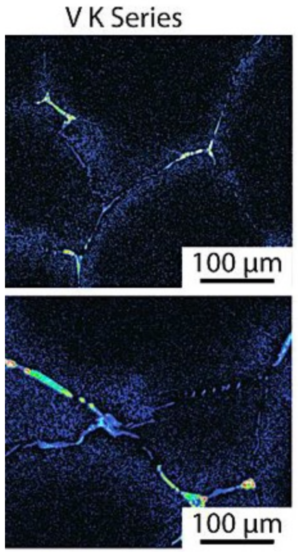


Densification



Microstructural heterogeneities

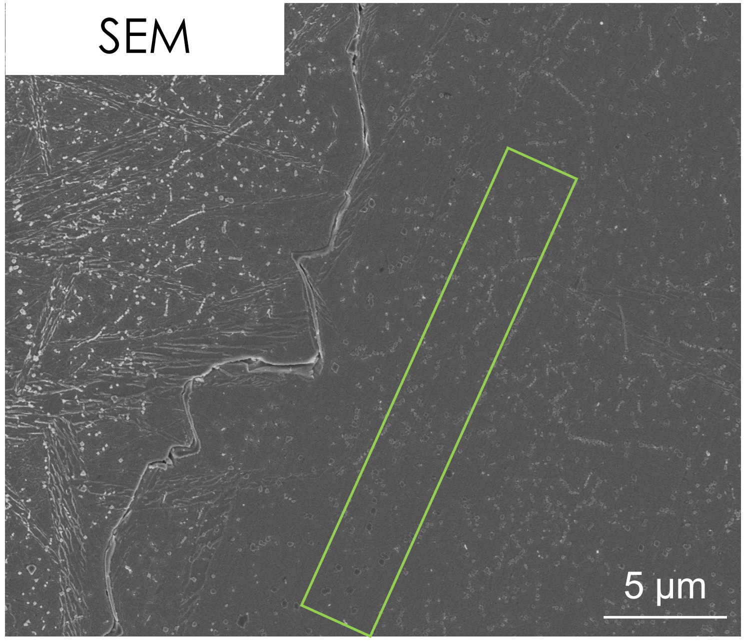


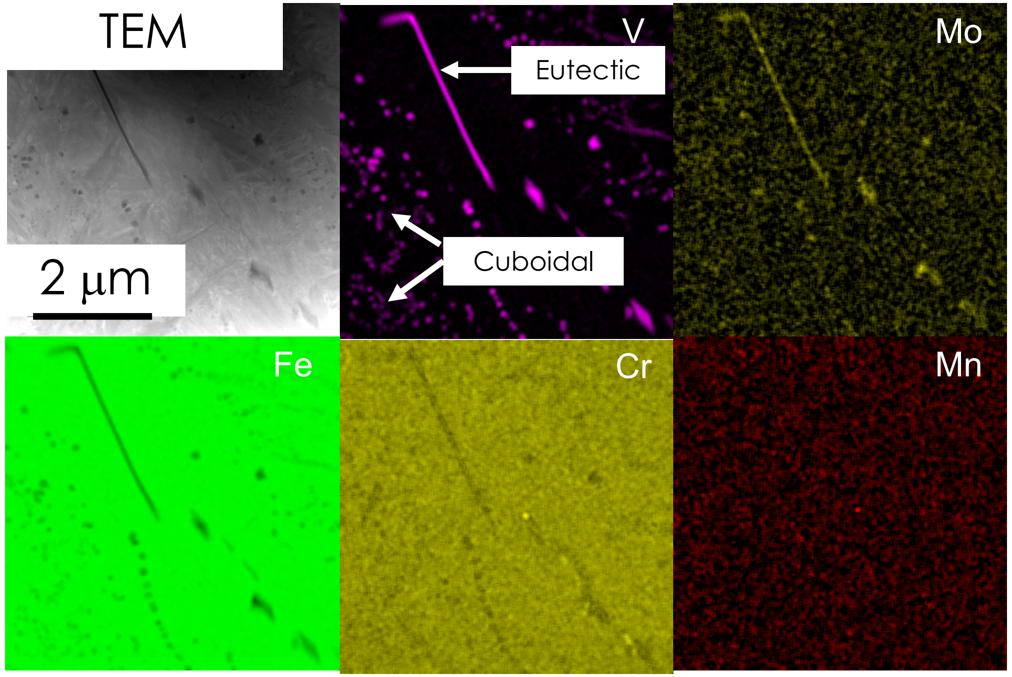


- Selection of process settings to achieve maximum densification without **shape change**
- Density >98% in as-sintered condition
- Supersolidus liquid phase sintering (SLPS) results in solute segregation that can form deleterious grain boundary carbides
- HIP & Heat Treatment

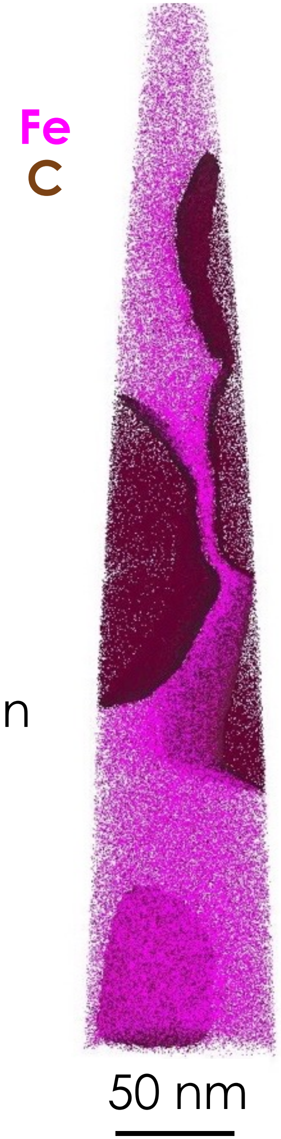
Nandwana et al. *Additive Manufacturing* 2020

Eutectic and Cuboidal Carbides Identified



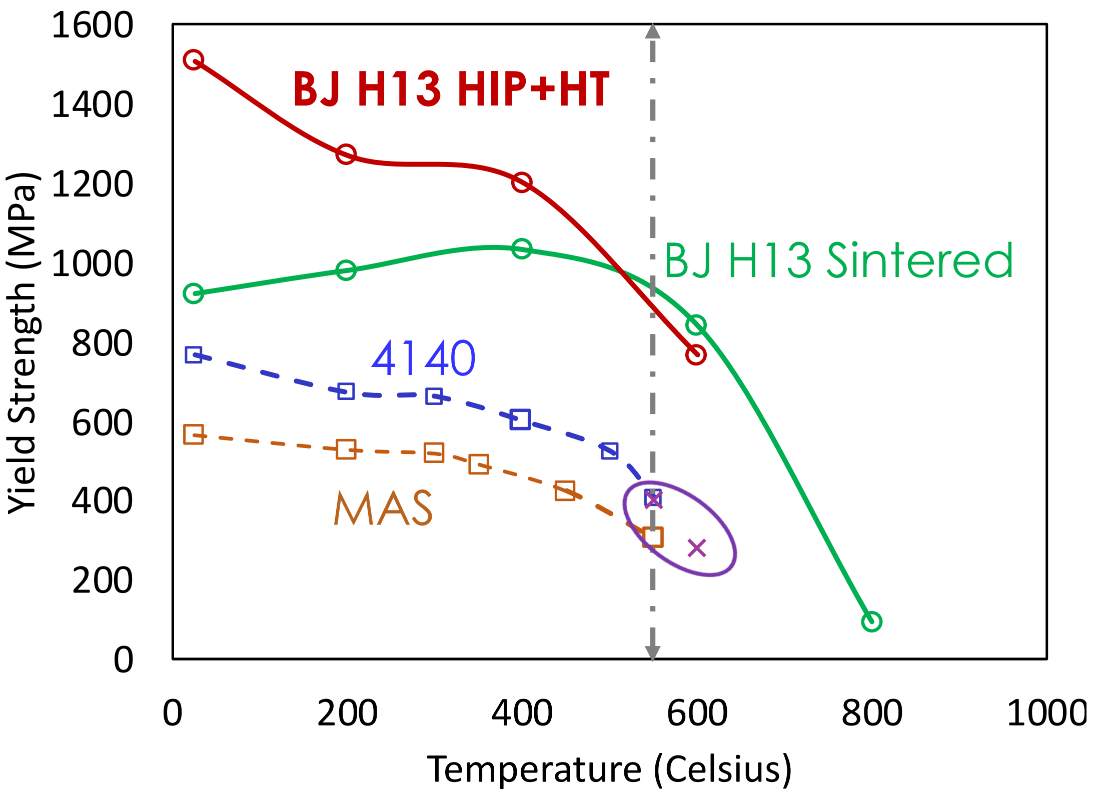


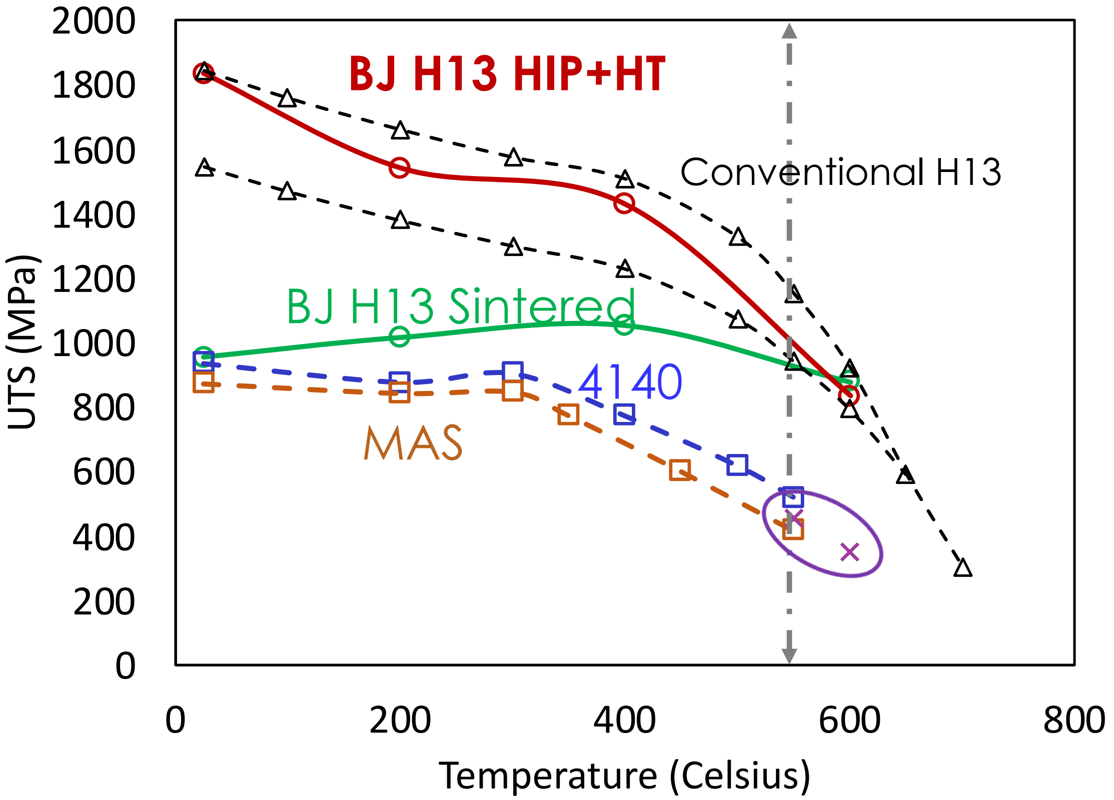
Atom Probe



- Distinct carbide morphologies seen – eutectic and cuboidal **MX Carbides**
- Eutectic carbides form during solidification of liquid phase – observed for the first time in H13 and dependent on carbon pickup during binder jetting
- Discrete cuboidal carbides form during solid state transformation and can be interconnected – impact material ductility
- Homogenization treatments required

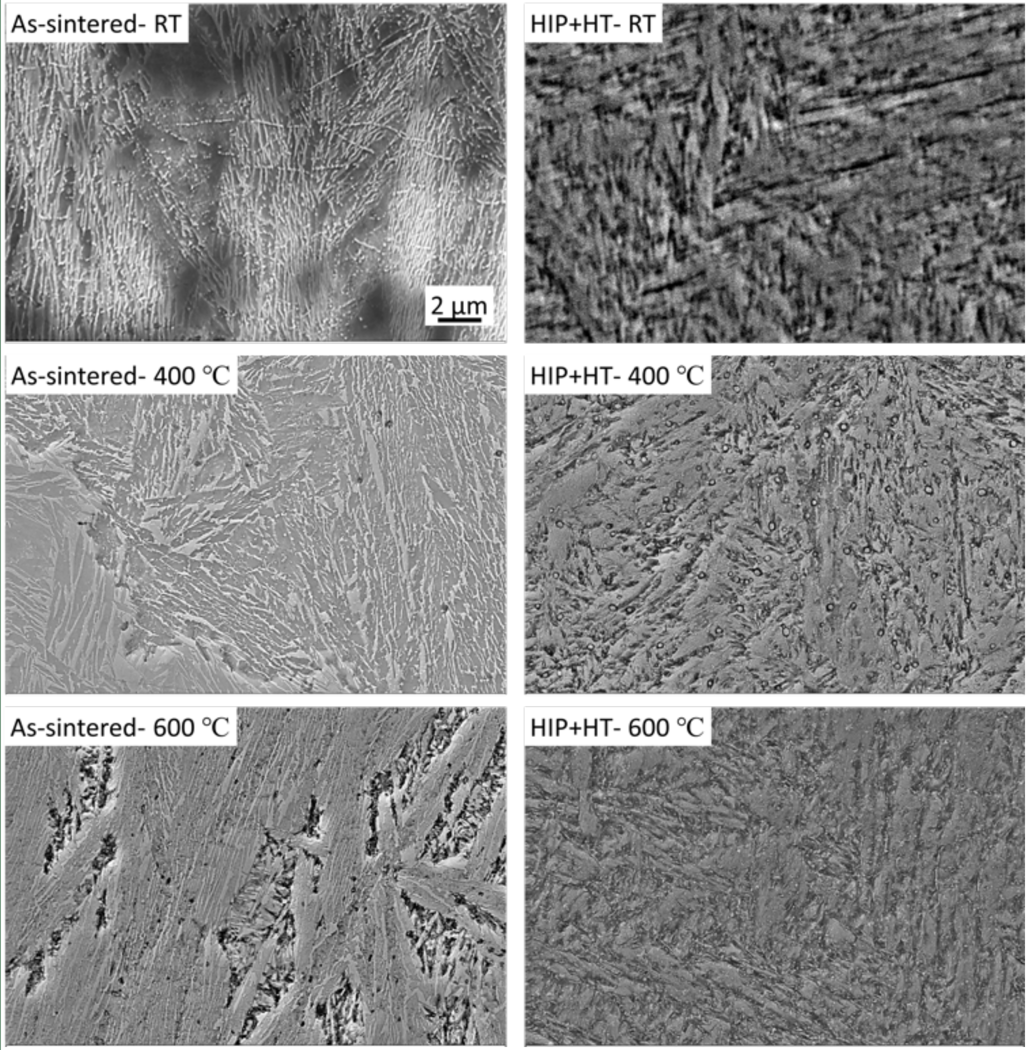
Tensile Strength of Binder Jet H13 Exceeds 4140 & MAS



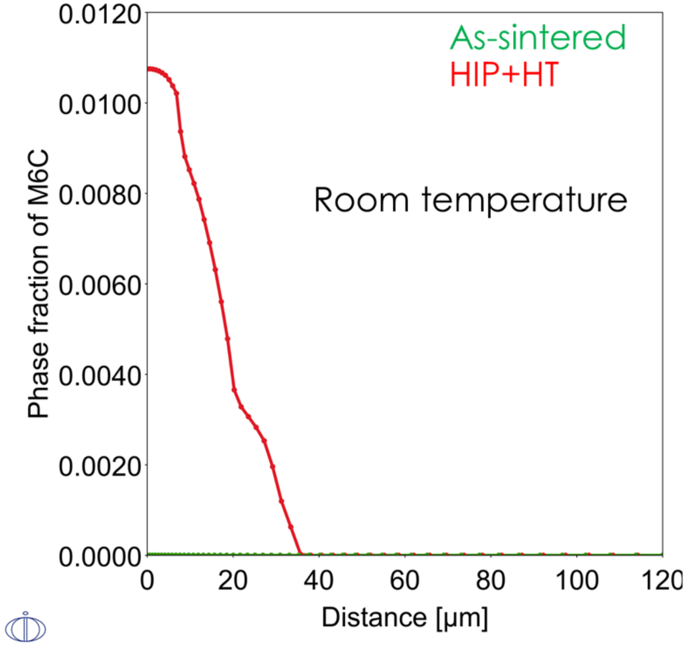


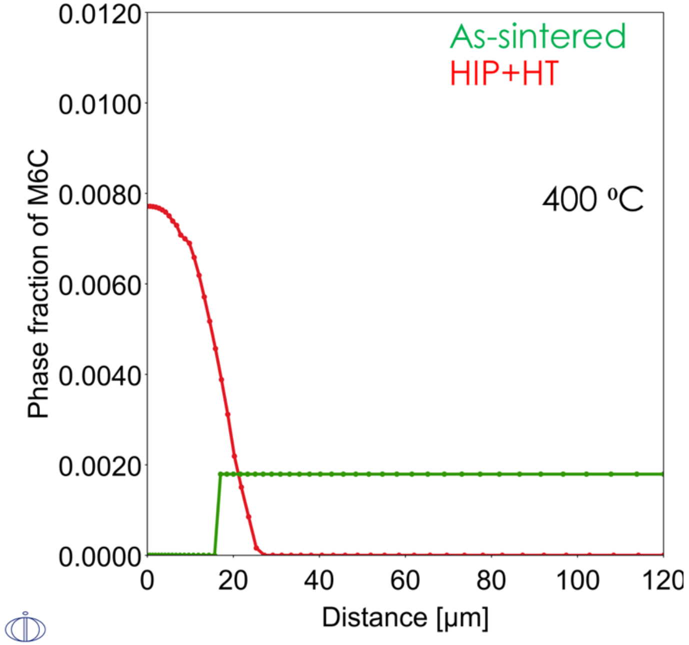
- At 500 °C, binder jet AM H13 subjected to HIP+HT has ~2x the UTS of 4140
- Substantial drop in UTS of binder jet H13 between 400 °C and 600 °C

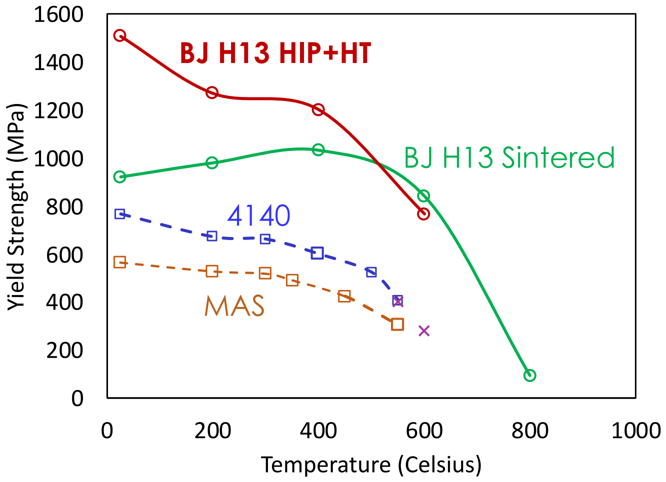
Thermodynamic Modeling of Microstructural Evolution



Starting as-sintered microstructure very different from HIP+HT microstructure



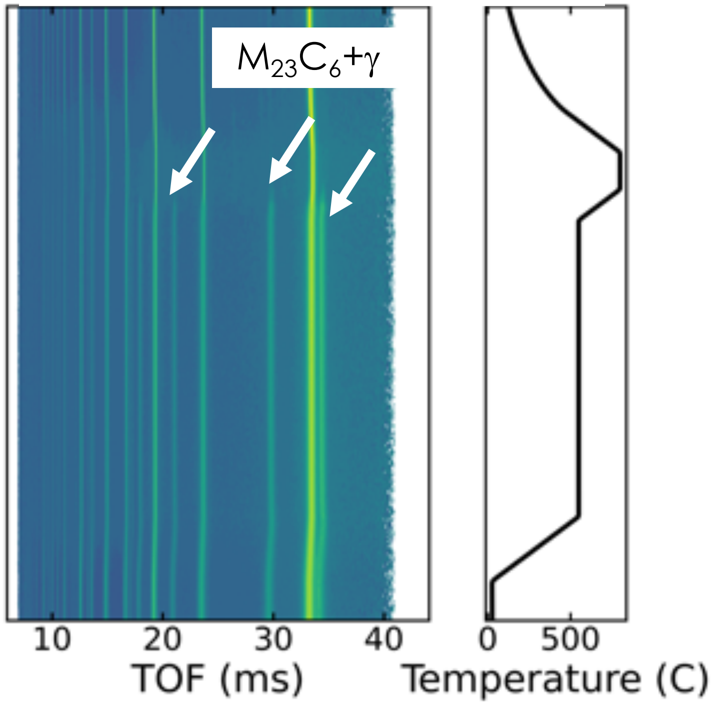




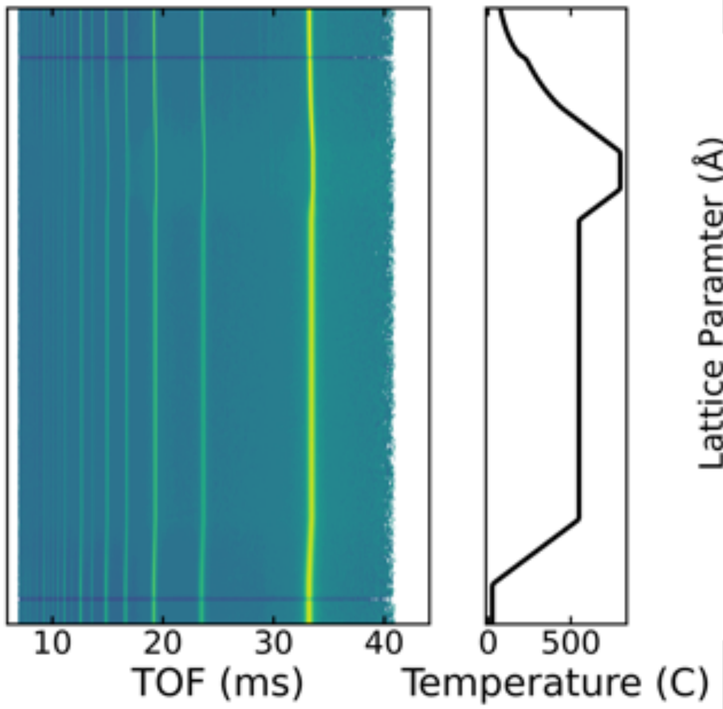
The increase in YS of as-sintered H13 and reduction on YS of H13 explained by CALPHAD modeling

Neutron Diffraction Reveals Phase Evolution During Heat Treatment

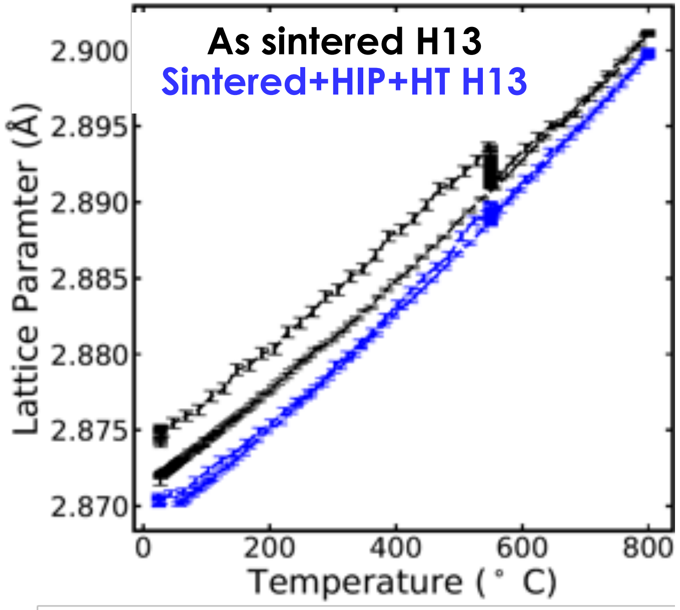
As Sintered H13



Sintered+HIP+HT

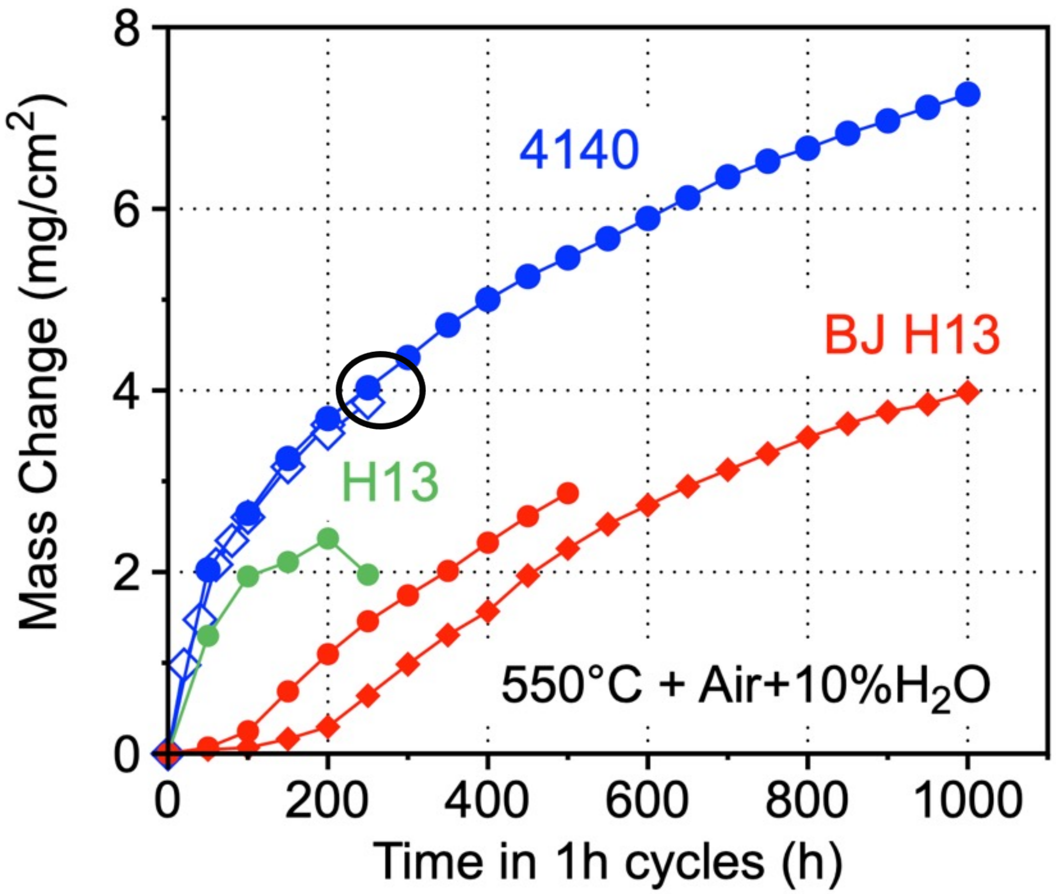


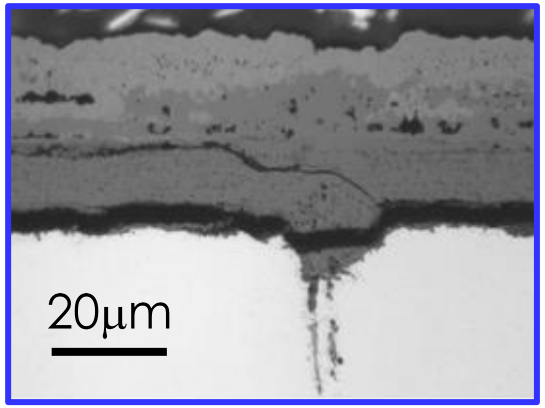
Lattice Parameter



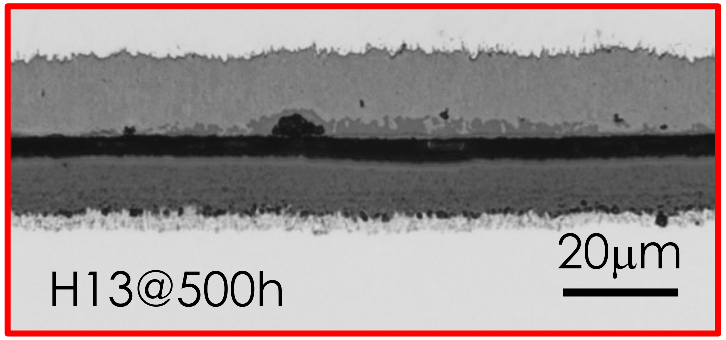
- ➢ Binder jet H13 in as-sintered and HIP+HT condition subjected to phase evolution as a function of increasing temperature
- ➢ As sintered condition has additional FCC peaks – retained austenite and M23C6 carbides
- ➢ Reduction in lattice parameter indicative of homogenization – analysis ongoing

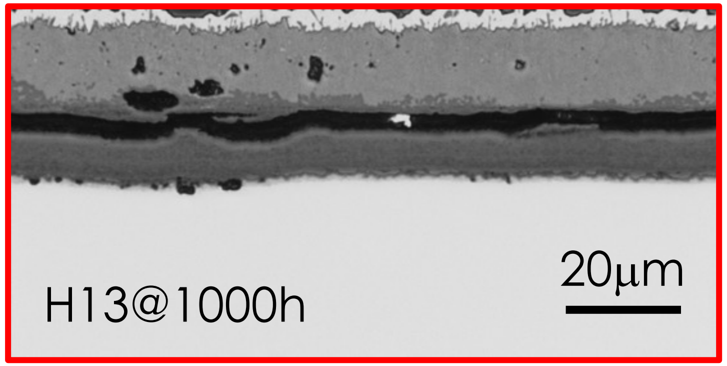
Better 550°C Cyclic Oxidation Performance for Binder Jet H13 Compared to 4140 & Wrought H13





4140@250h

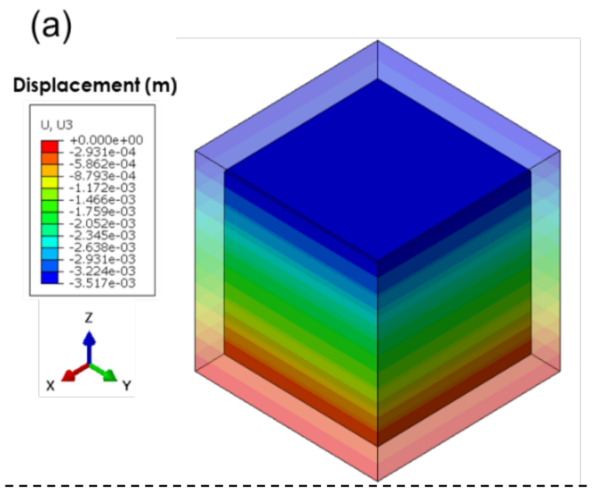


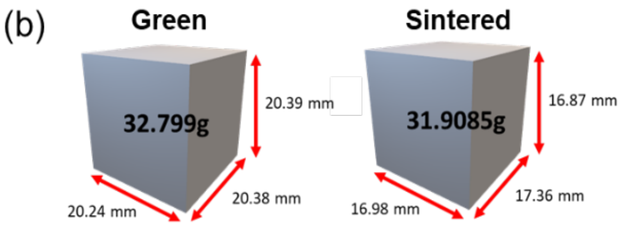


- Protective behavior for 100-200h results in lower mass changes compared to wrought H13 or 4140
- Similar thinner duplex oxide scale for both 4140 and H13

Task 4B: Correlating Powder Bed Density and Part Shrinkage

✓ **Continuum scale shrinkage model**

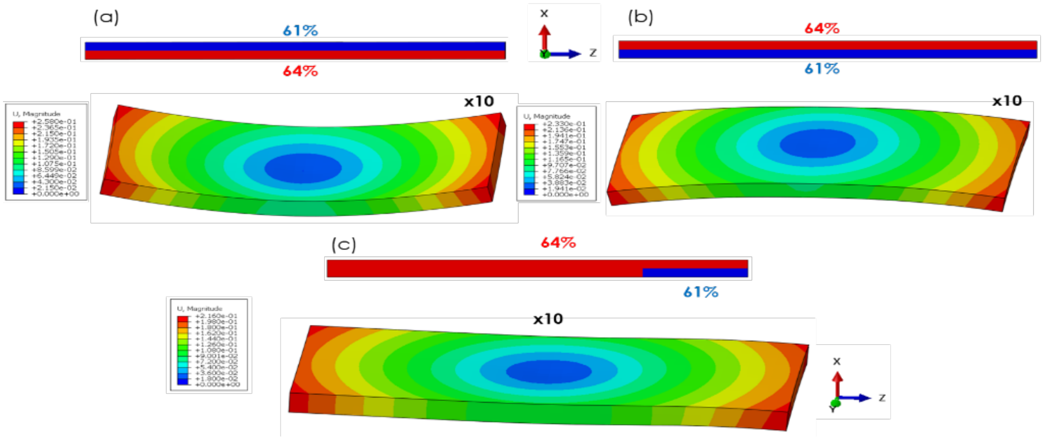




(c)

Exp.	Sim.	%Error
16.98	17.06	0.48%
17.36	17.06	-1.72%
16.87	16.80	-0.40%

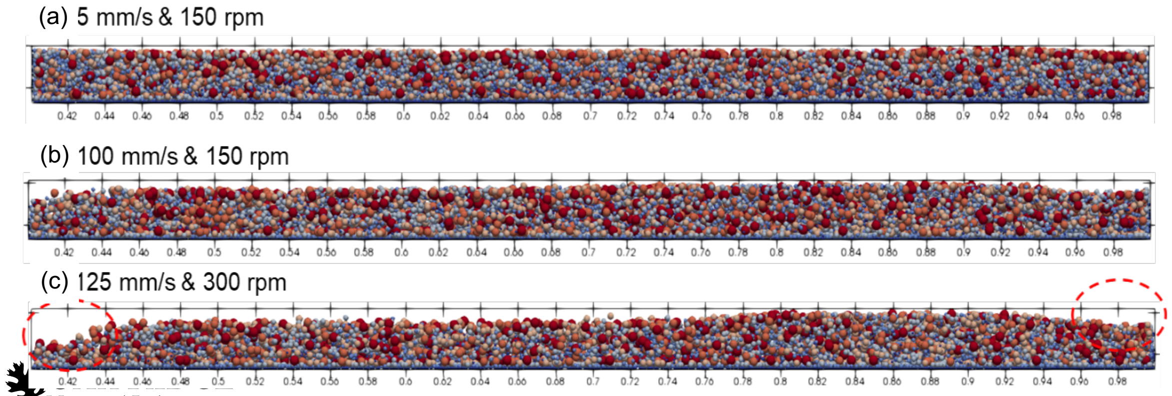
✓ **Effect of anisotropic packing density on part deformation**



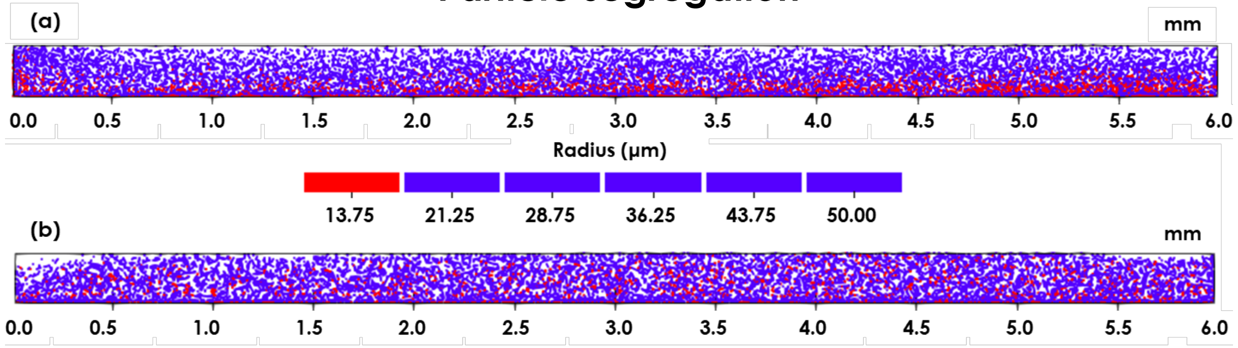
Part-scale simulation (FEM)

Particle-scale simulation (DEM)

✓ **Surface roughness**



✓ **Particle segregation**



Responses to Previous years Reviewer's comments

- Project was not reviewed last year

Remaining Challenges and Barriers

- Long-term thermal stability
- Carbon control during binder jet AM
- Determination of fatigue and creep behavior
- Print, sinter and machine piston to final geometry
- Dimensional control and repeatability over builds
- Impact of cheaper powder feedstock on the process such as water atomized powders
- New piston designs with internal cooling channels

Collaboration and Coordination

- **Program Lead**
  - Oak Ridge National Laboratory (ORNL)
    - Spallation Neutron Source (SNS)
    - Center for Nanophase Materials Sciences (CNMS)
    - Manufacturing Demonstration Facility (MDF)
- **Program Partners**
  - Thrust 4A - Pacific Northwest National Laboratory (PNNL)
    - Atom Probe and Transmission Electron Microscopy
  - Thrust 4B - Oak Ridge National Laboratory (ORNL)
    - Distortion calculations during sintering
- **Other Partners**
  - Zeiss
  - New FY21 collab with Army GVSC for printed pistons

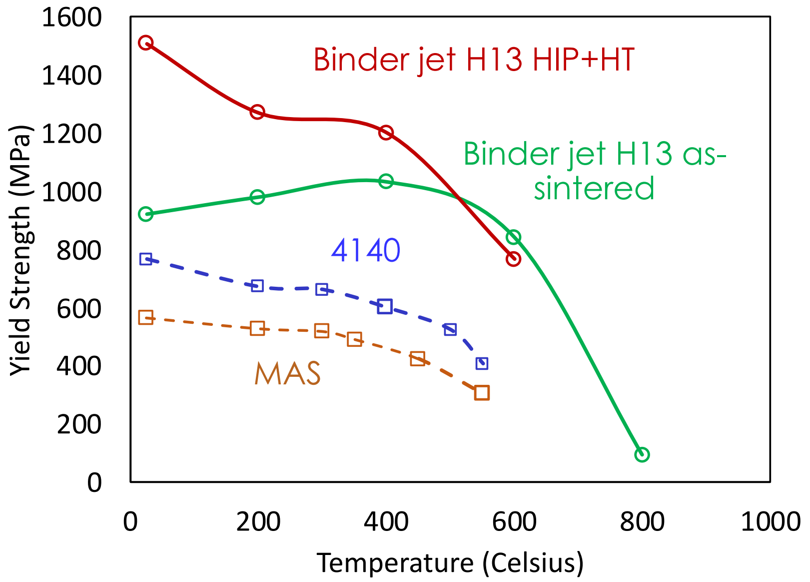
Proposed Future Research

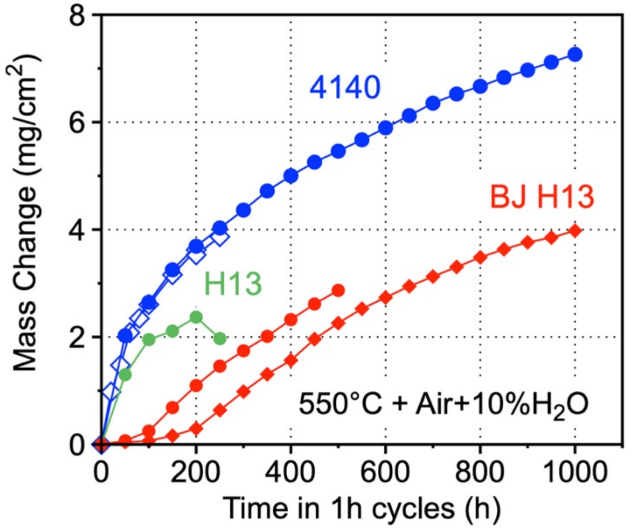
- Evaluate the effects of **long-term thermal exposure** on material properties
- Determination of the mechanism resulting in superior oxidation performance of binder jet H13 compared to wrought H13
- Leverage characterization techniques to refine ICME approach to make the models predictive in nature
- Thermal properties for piston applications
- Based on the effect of long-term thermal exposure on material properties and microstructure, either new heat treatments will be designed using the ICME approach or modifications to the alloy chemistry will be made in collaboration with **Task 2A2**

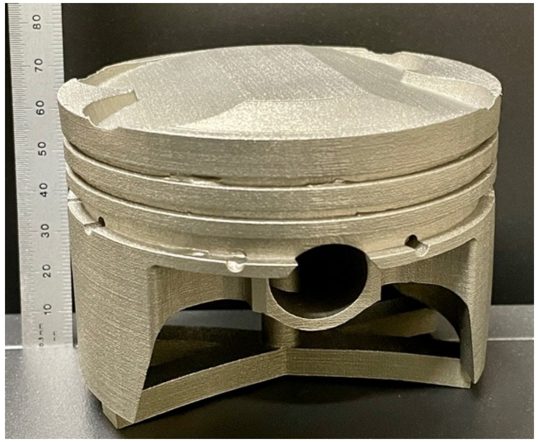
Any proposed future work is subject to change based on funding levels

Summary

- **Benefits of AM**: Eliminate welding, minimize machining, internal cooling channels & design flexibility (light weight designs)
- Sintered binder jet AM piston demonstrated using SS316
- Commercial steel (H13) used for binder jet AM
- Tensile strength better than 4140 and MAS (~1.8x higher YS at 550° C)
- 50% reduction in mass gain during oxidation compared to 4140



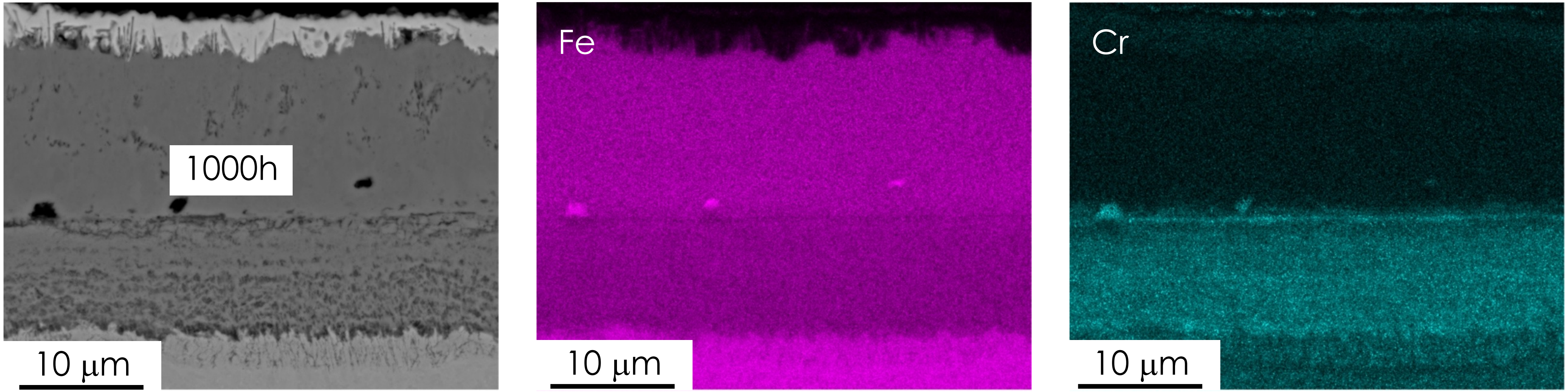




Proof of Concept:
Sintered Stainless Steel
316 Piston

Technical Back-Up Slides

Binder Jet H13 forms a Dense Oxide Scale at 550 °C – No Spallation After 1000h



SEM EDS showing an Fe and Cr rich complex oxide formed in binder jet H13 after 1000h of exposure at 550 °C to a 10% H_2O + Air