SAND2022-2367C

Heat Treatment Effects on Mechanical Properties of Wire Arc Additive Manufactured and Electron Beam Additive Manufactured Ti-6Al-4V

Jonathan Pegues, Shaun Whetten,
Andrew B. Kustas, William Dannemann,
Tyler Chilson

Sandia National Laboratories

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

About the Presenter

- **Jonathan Pegues, Sandia National Laboratories (SNL)**
  - **R&D Mechanical Engineering, SNL, Coatings & AM**
  - **PhD. Mechanical Engineering, Auburn University**

- **Acknowledgements:** Luis Jauregui, John Williard, Priya Pathare, Jay Carroll, Christina Profazi, Johnathon Brehm, Jeier Yang, Dennis De Smet, Chuck Walker, Elliott Fowler, Elizabeth Huffman

- jwpegue@sandia.gov

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy National Nuclear Security Administration under contract DE-NA0003525

Sandia National Laboratories

Additive Manufacturing at SNL

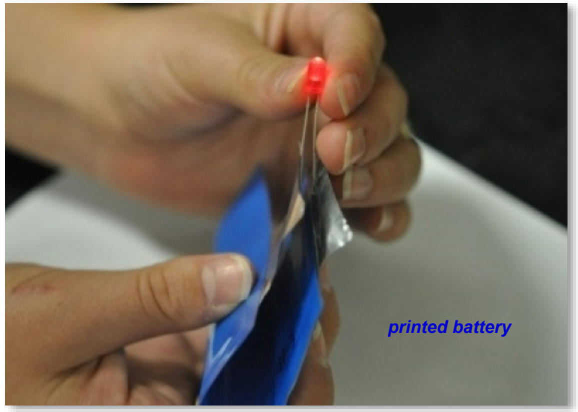
Reduce risk, accelerate development

- Restore manufacturing capability
- Simplify assembly & processing
- Prototypes, test hardware, tooling & fixturing

Add value

- Design & optimize for performance, not mfg
  - Complex freeforms, internal structures, integration
- Engineered materials
  - Gradient compositions
  - Microstructure optimization & control
  - Multi-material integration
    - "print everything inside the box, not just the box"


Sandia telescope


printed battery

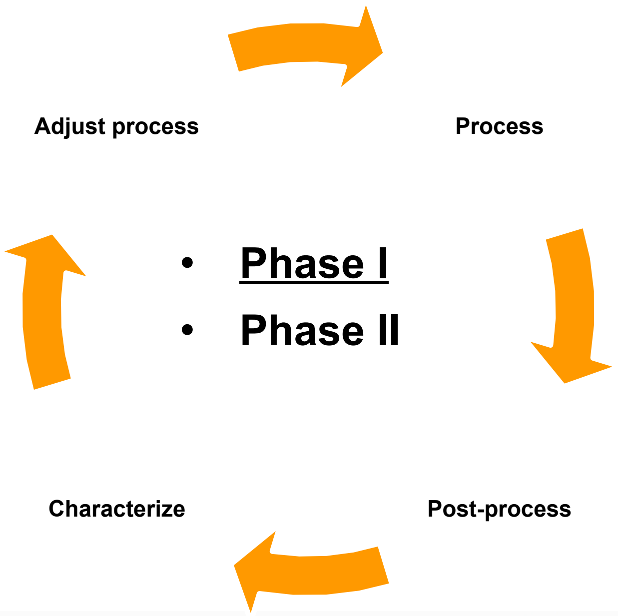

full scale additive weapon mock-up

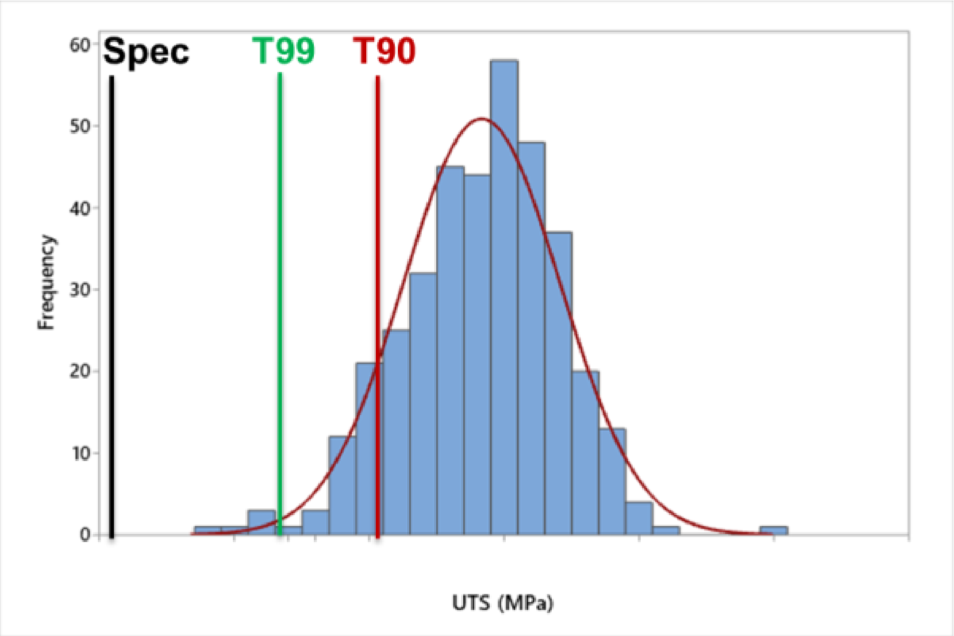
Continually growing interest across Sandia missions

W-DED: Background

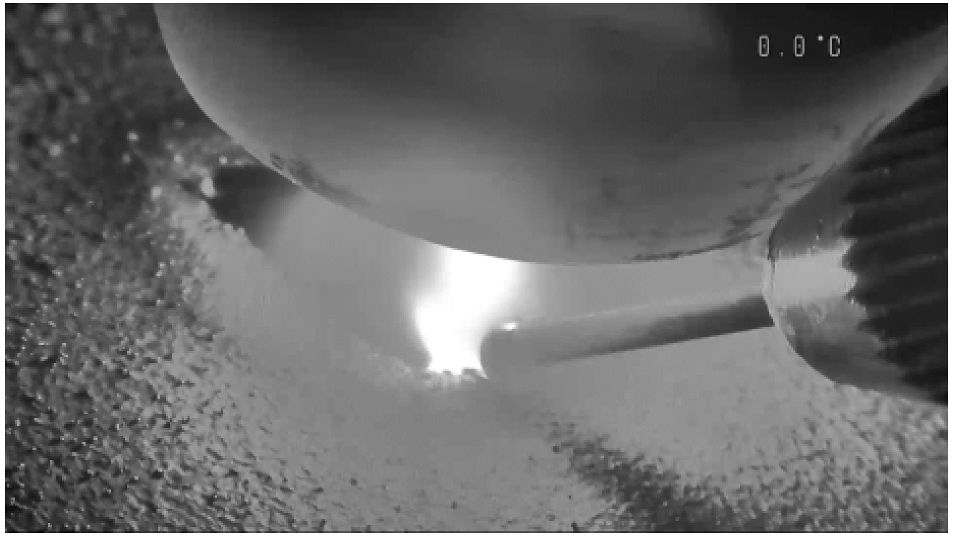
Objective: Provide <u>statistically validated</u> material specs and design margins for W-DED Ti-6Al-4V products

- Balance need of rapid testing and establishing statistically AND structurally relevant data
- Provide guidance to stakeholders with clear pathway for process qualification cycle of W-DED products

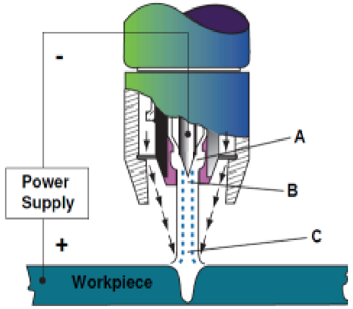




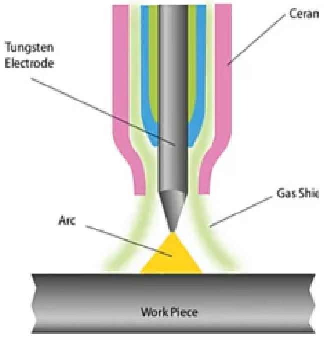
Hybrid WAAM



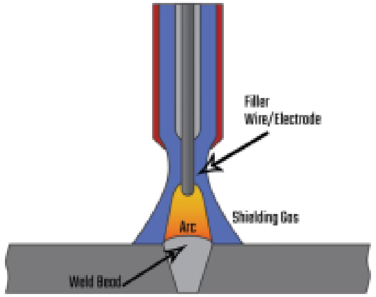
Meltview monitoring camera



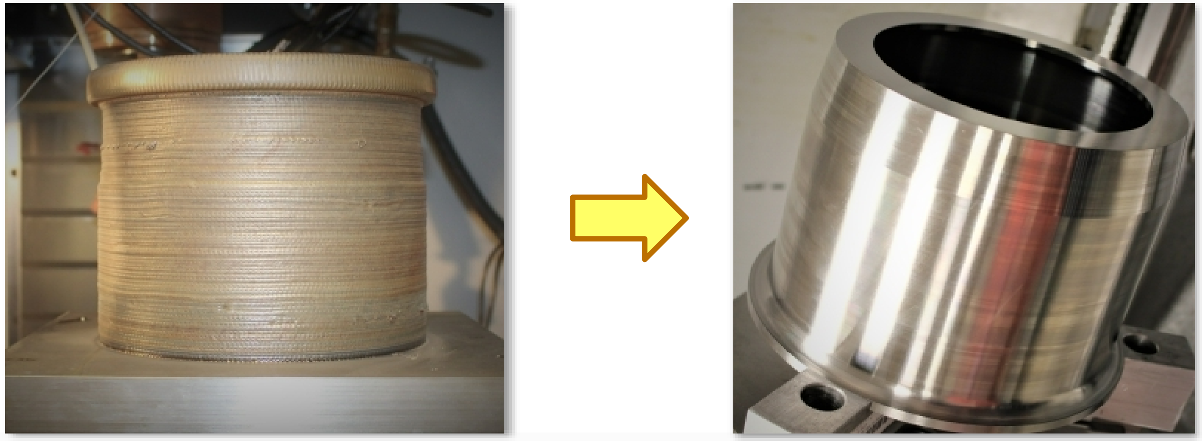
Plasma Arc



Tungsten Arc

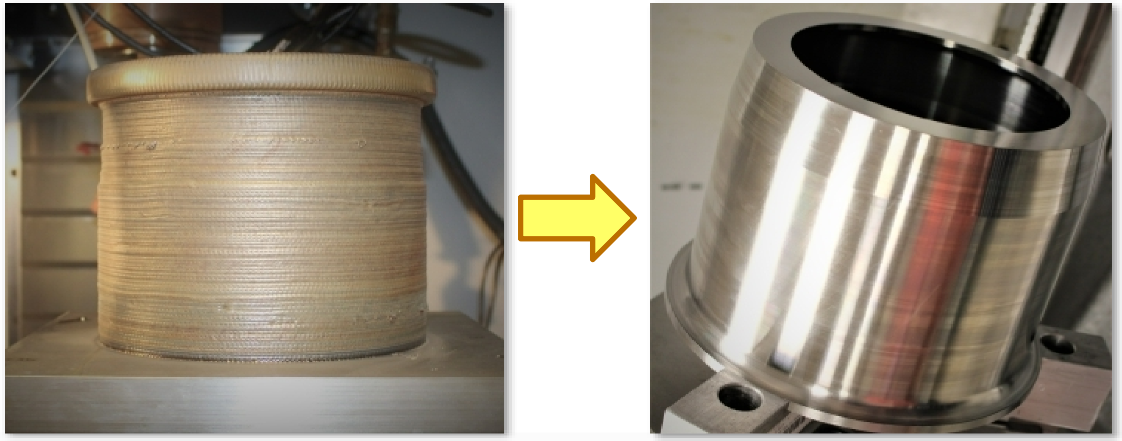


Metal Arc



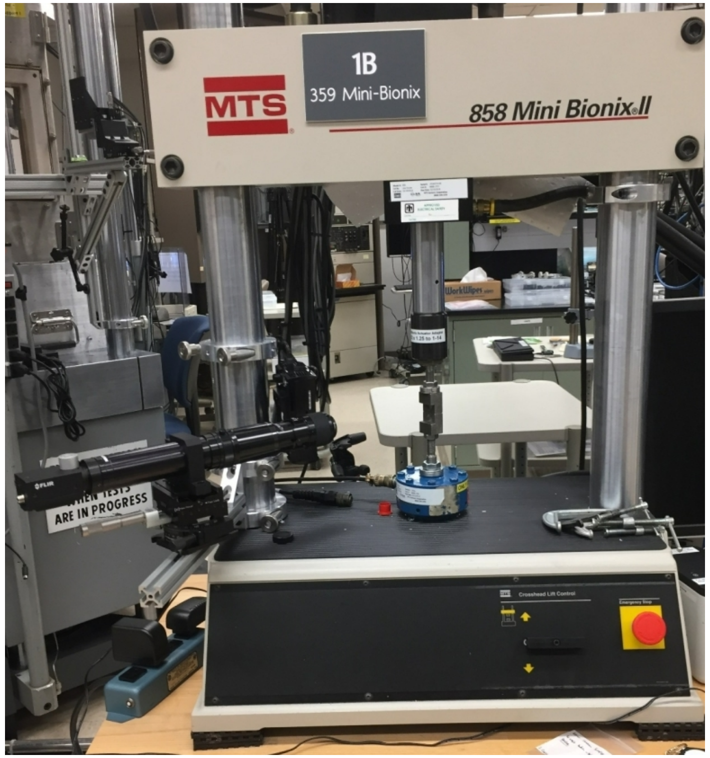
EBAM - Sciaky

Sciaky Image credit: https://www.sciaky.com/additive-manufacturing/industrial-metal-3d-printers



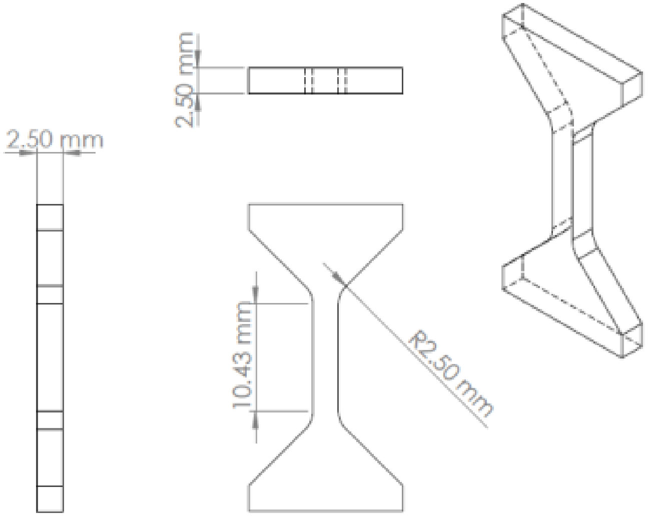
“High Throughput Testing”

MTS: 858 5-kip frame

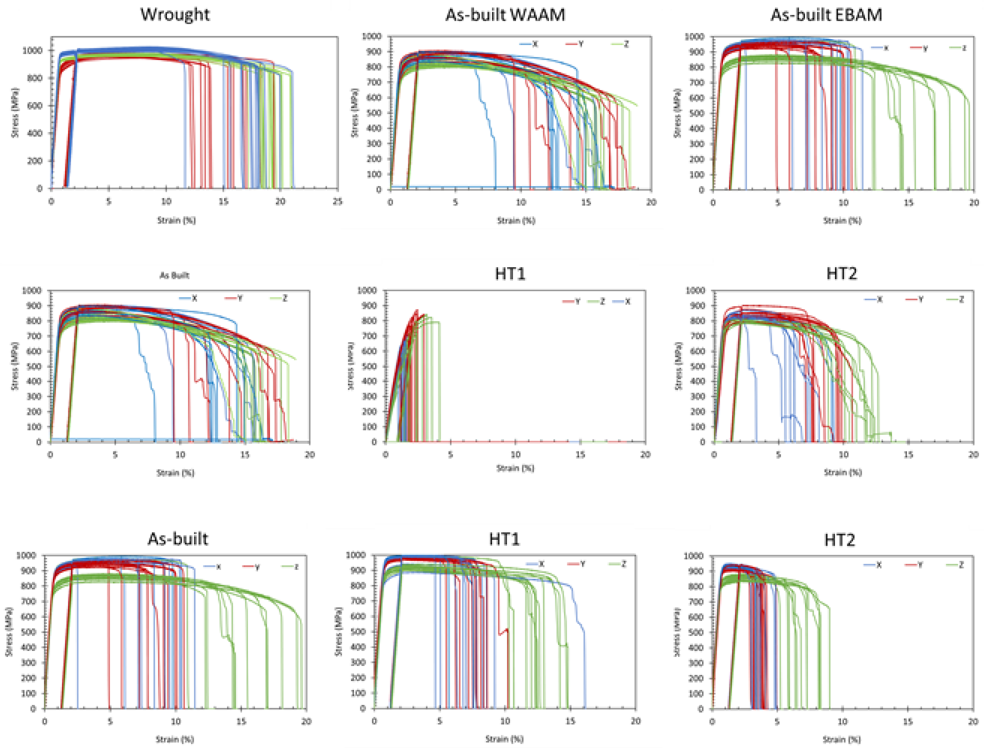


- Displacement rate 0.01 mm/s
- FLIR 90 fps, 4.1 Mpix camera

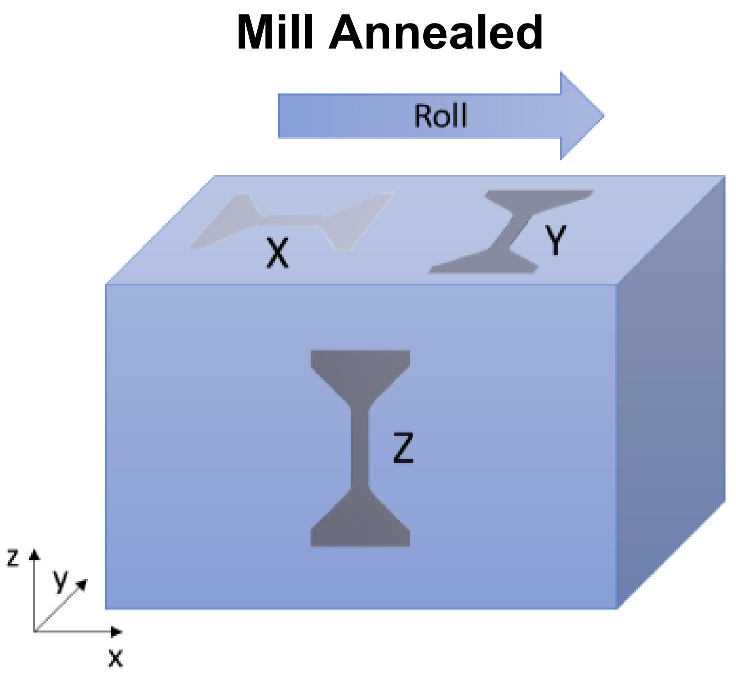
High Throughput Specimen Geometry

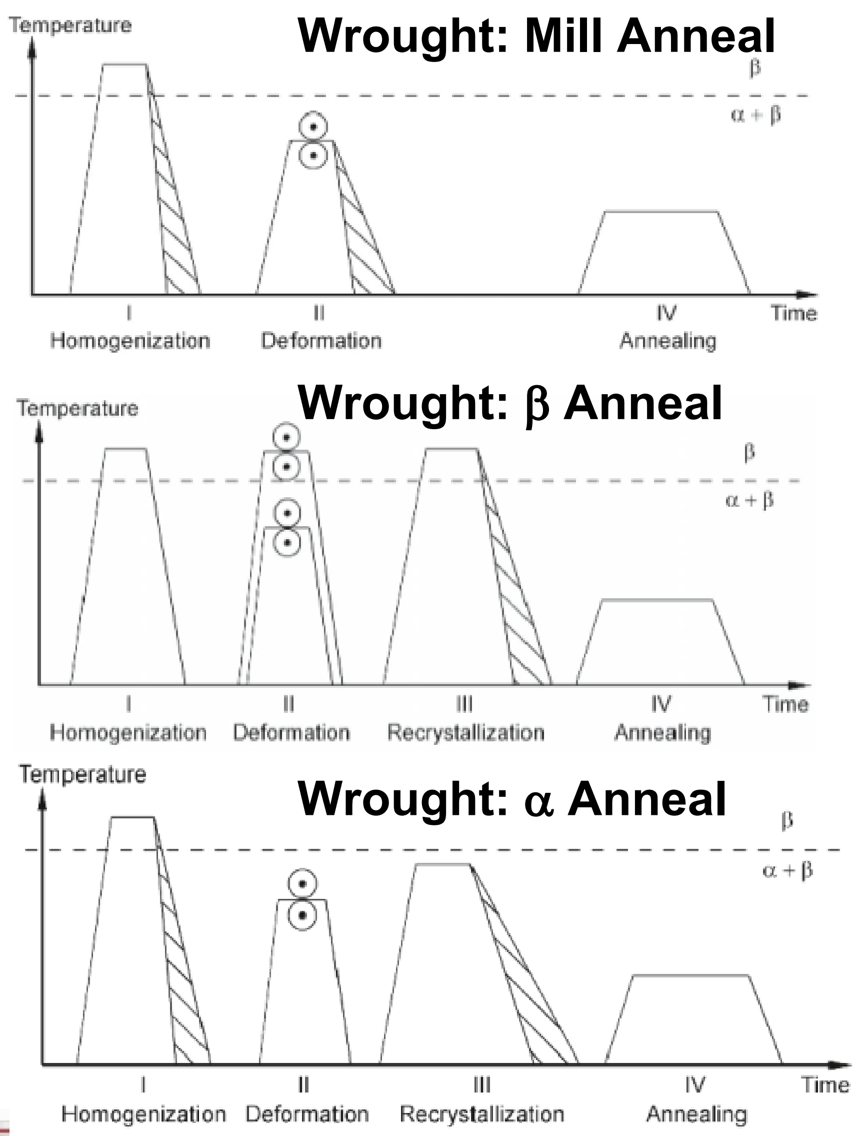


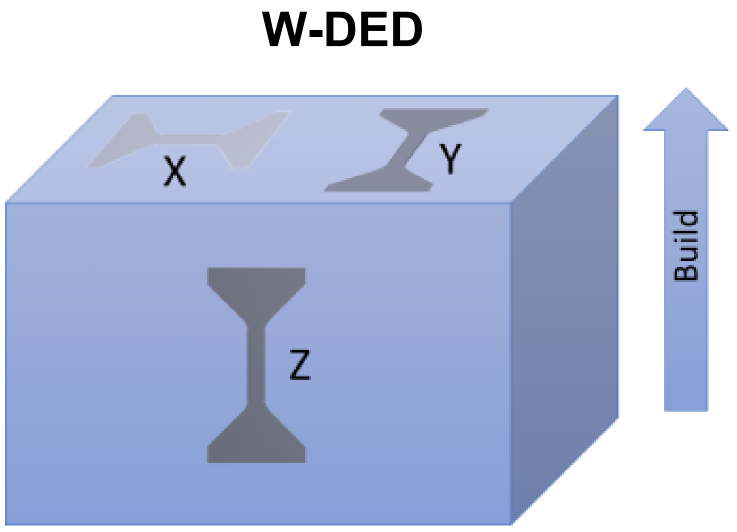
Rapid development of statistically relevant tensile data



Conventional vs. Additive Manufactured







Conventional Process
- Material formed from bulk feedstock
- Microstructure formed prior to geometry
- Well documented post-process effects and properties

AM Process
- Near net-shaped from wire feedstock
- Microstructure formed along with geometry
- High uncertainty in post-process effects and properties

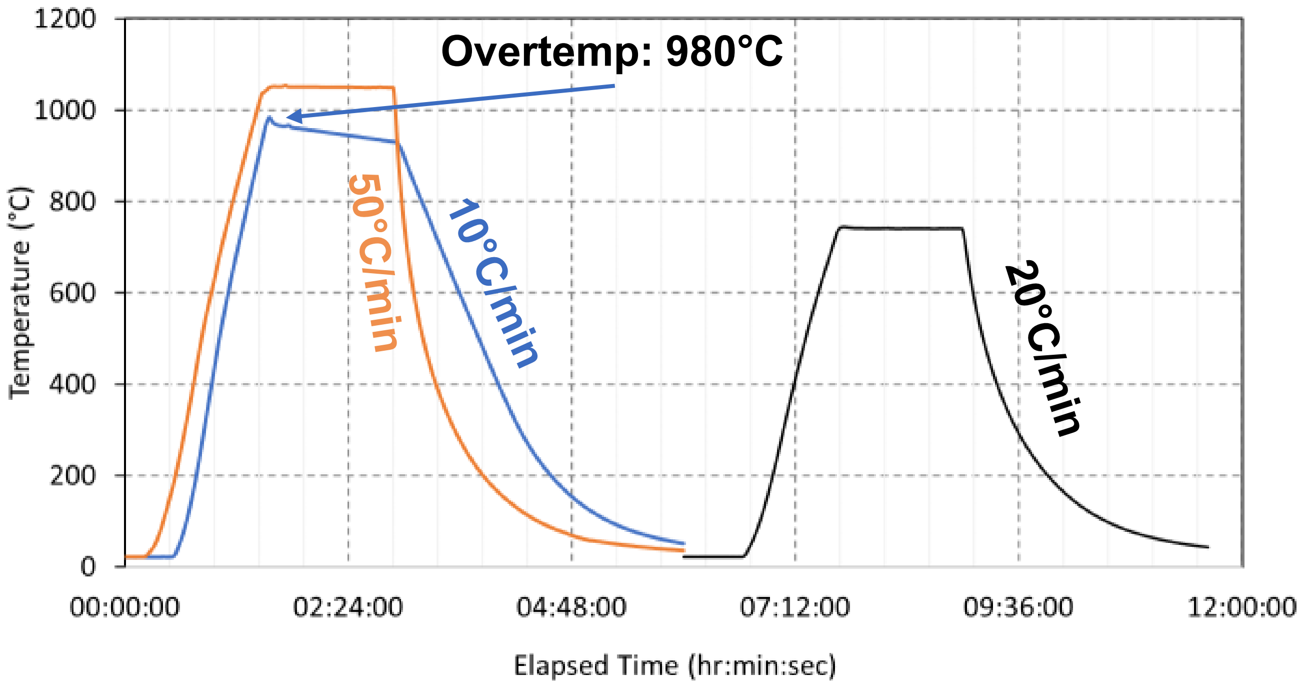
Heat Treatments

HT1: Beta anneal + Overage

Anneal at 1050°C for 1 hour, ArQ 725°C, 2 hour soak, Argon Quench

HT2: Alpha/Beta anneal + Overage

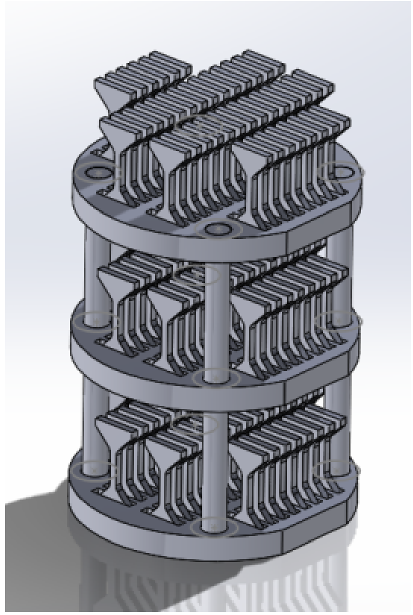
Anneal at 926°C for 1 hour, ArQ 725°C, 2 hour soak, Argon Quench



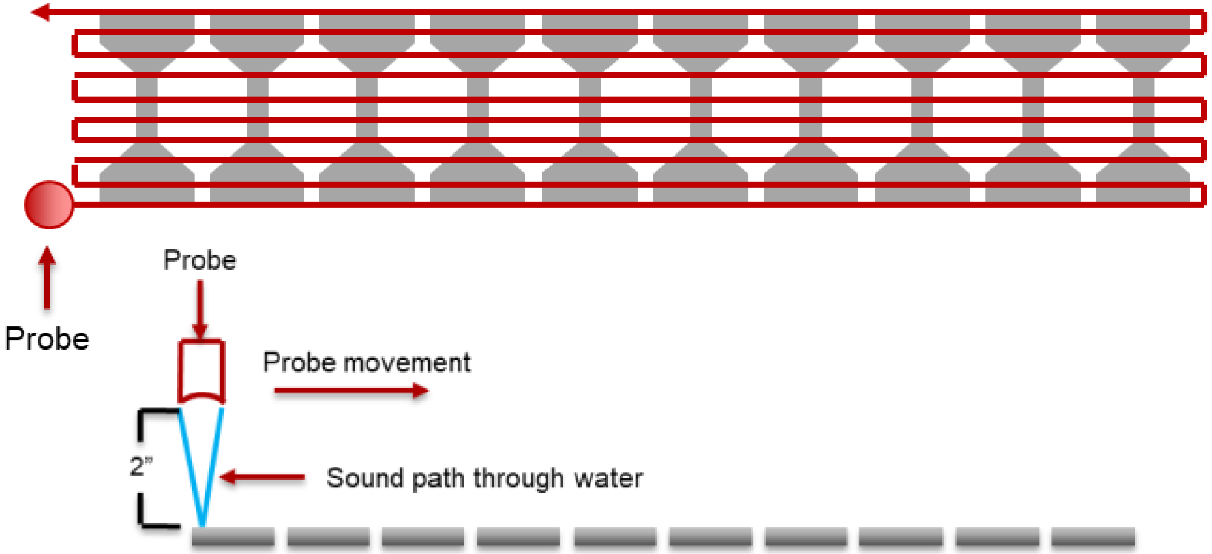
HIP: Hot Isostatic Pressing

920°C for 1 hour, 100 MPa, 2 hour soak

Used AIP6-30H (prior to refurbishment)

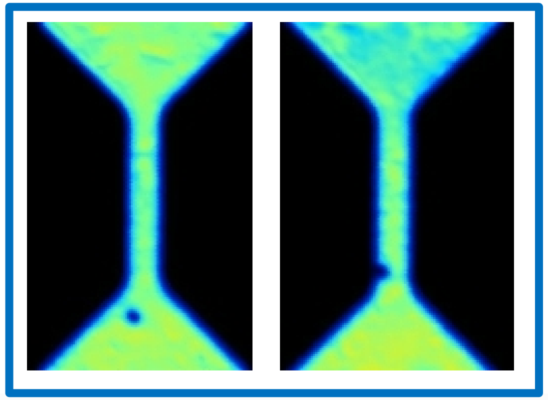


Immersion Ultrasonic Inspection

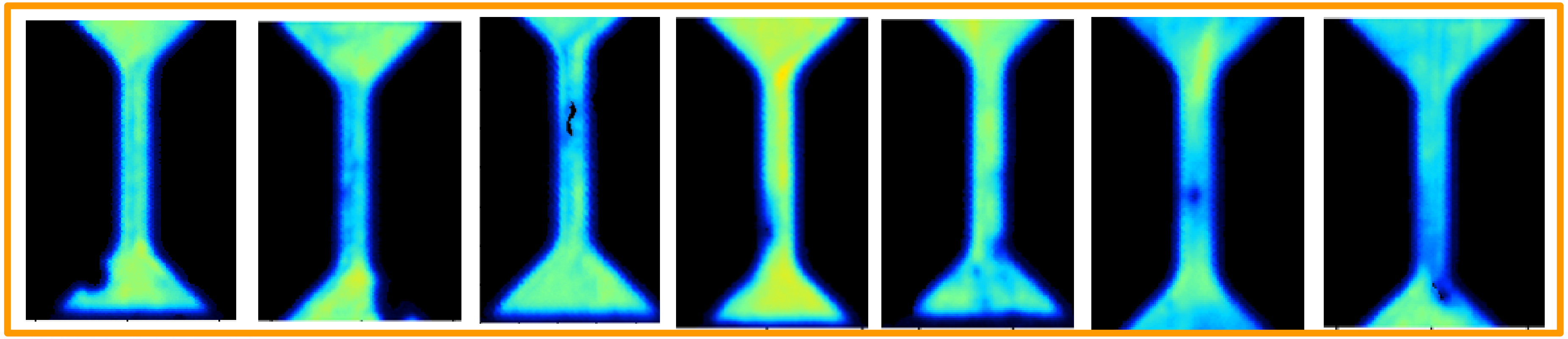


- Immersion inspections were performed from the etched surface.
- ~50 μm resolution and at a height of 50 mm above side being scanned
- No observable defects discovered for wrought material
- Low porosity observed for both WAAM & EBAM
- WAAM showed a slightly higher defect density

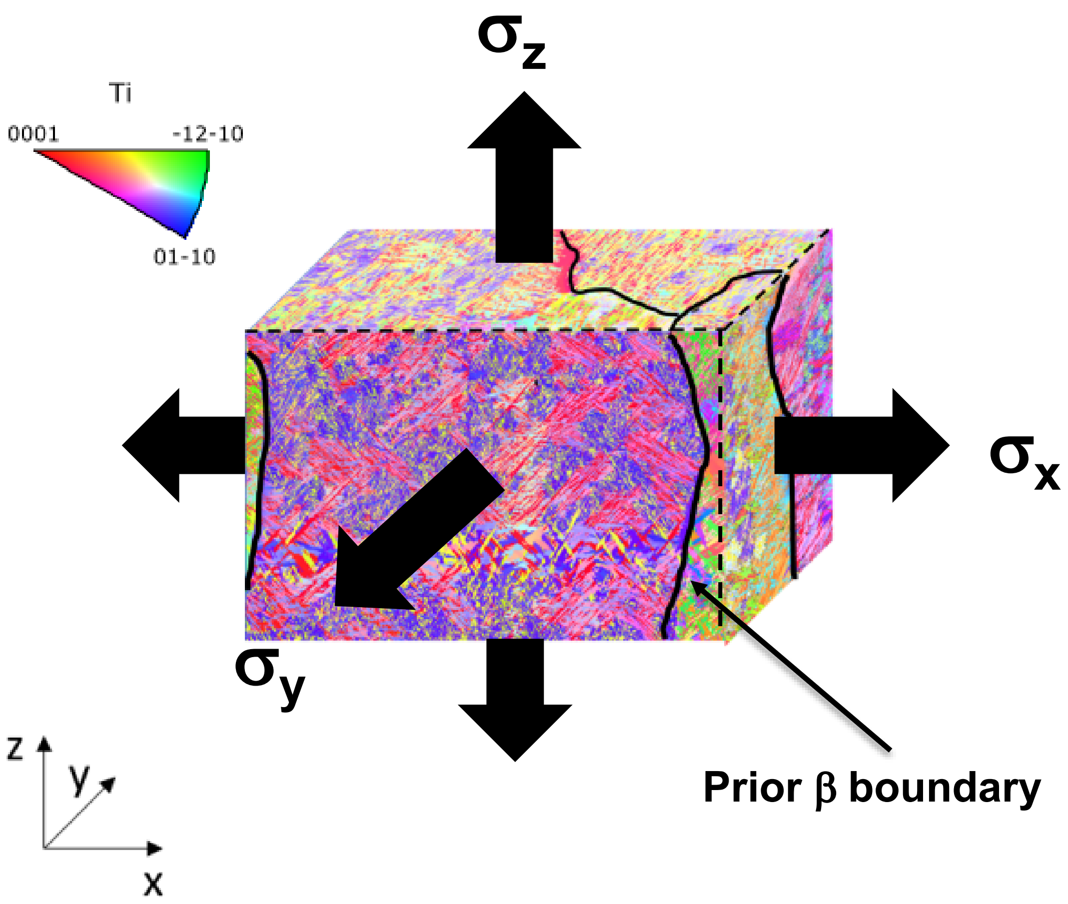
EBAM

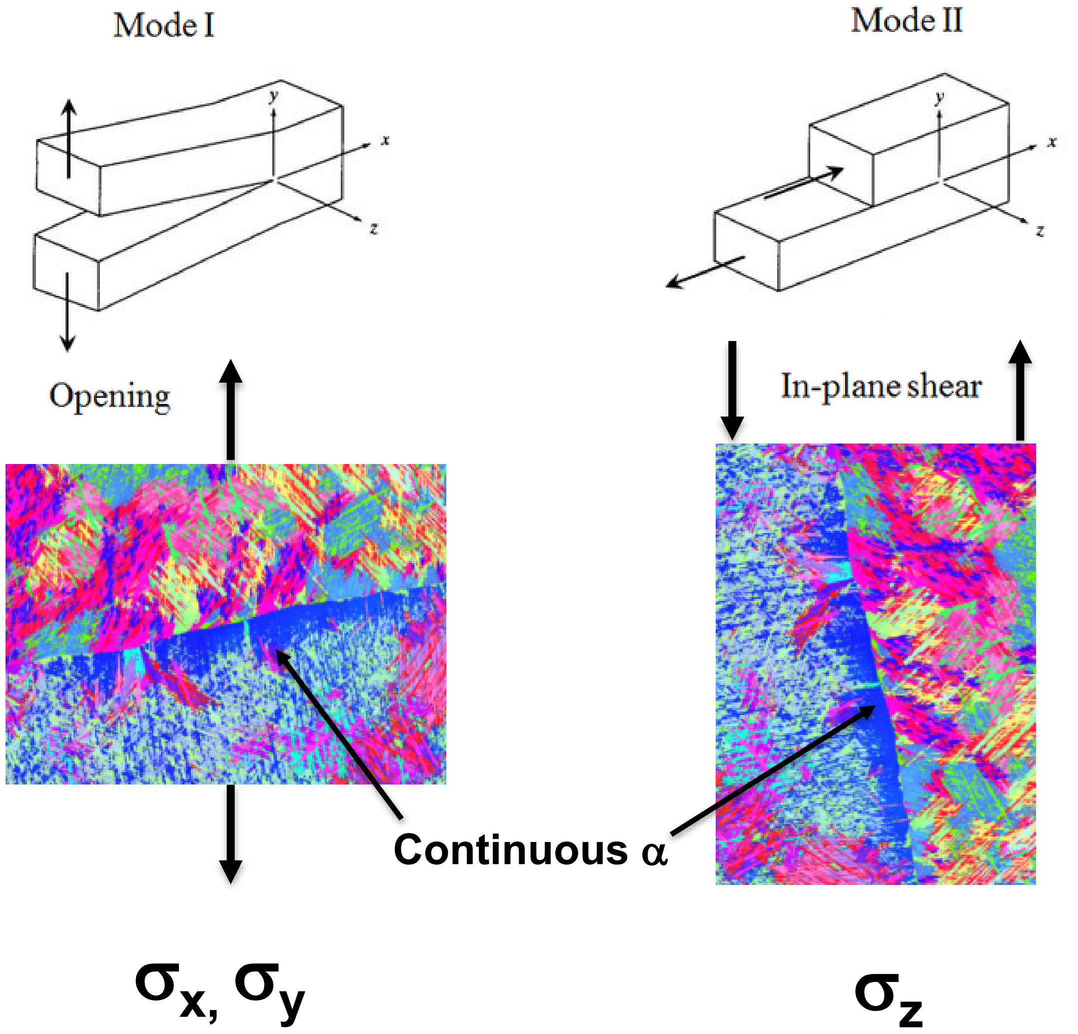


WAAM

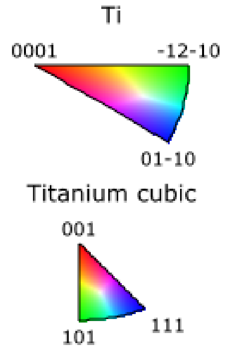


Anisotropy in W-DED





Wrought & As-built Microstructures

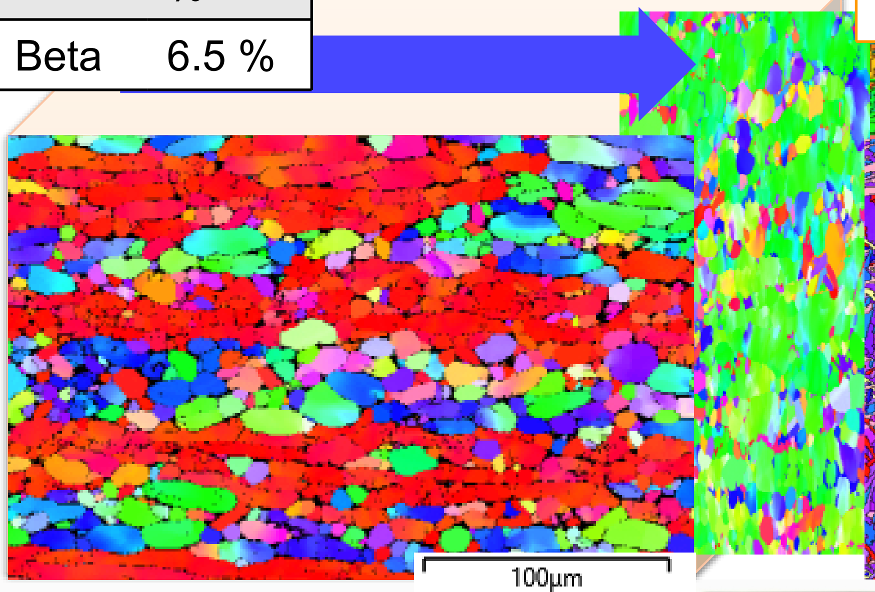


Wrought

Phase	At. %
Al	6.84
V	3.77
Fe	0.14

Phase	Fract.
Alpha	93.4 %
Beta	6.5 %

	Average (mm)	Std (mm)
Minor	4.07	3.50
Major	7.46	7.59

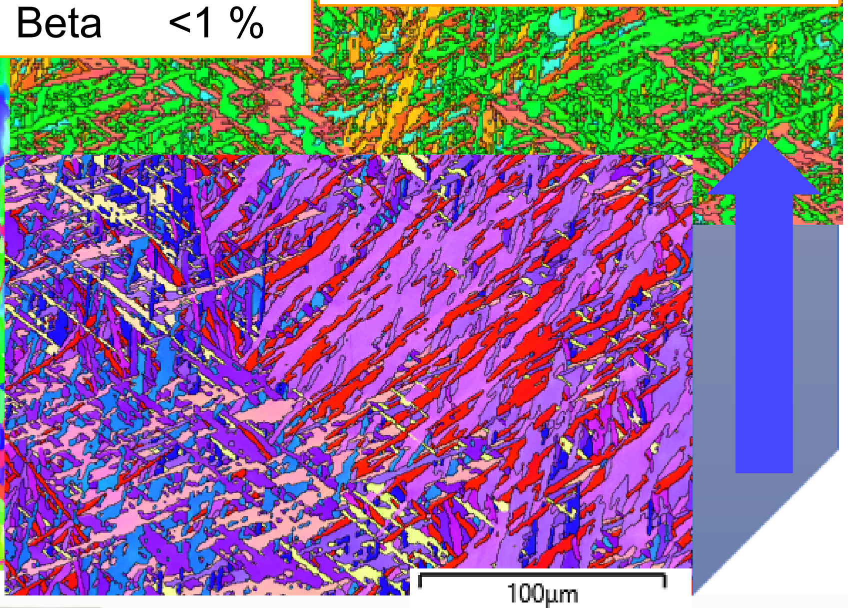


WAAM

Phase	At. %
Al	6.05
V	3.68
Fe	0.12

Phase	Fract.
Alpha	99 %
Beta	<1 %

	Average (mm)	Std (mm)
Minor	1.67	0.89
Major	6.18	5.49

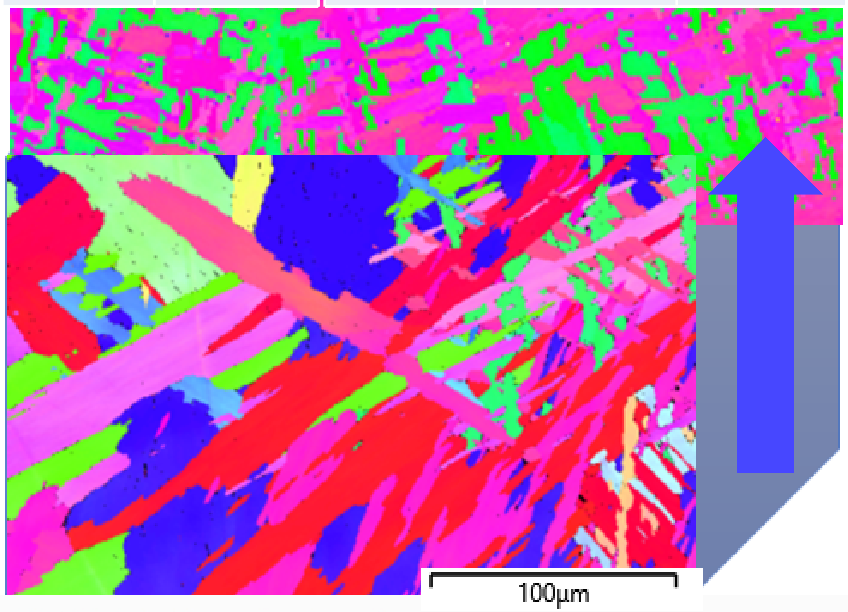


EBAM

Phase	At. %
Al	6.78
V	3.74
Fe	0.23

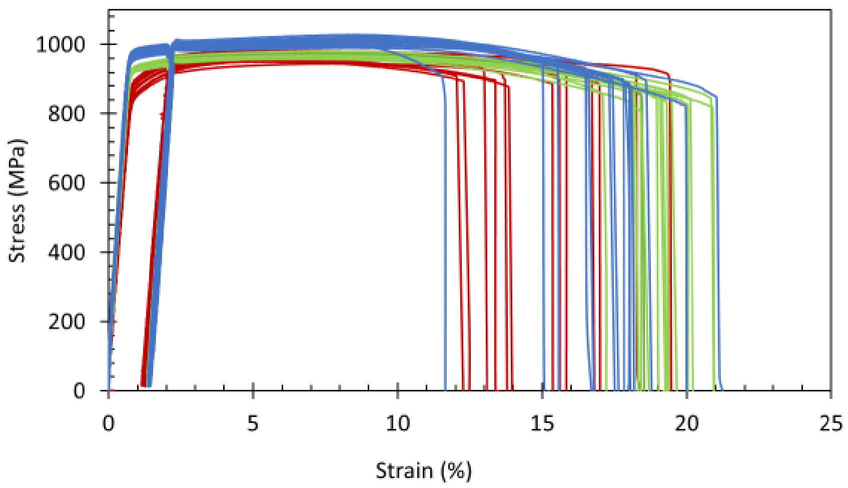
Phase	Fract.
Alpha	99 %
Beta	<1 %

	Average (µm)	Std (µm)
Minor	13.36	9.87
Major	37.81	29.88

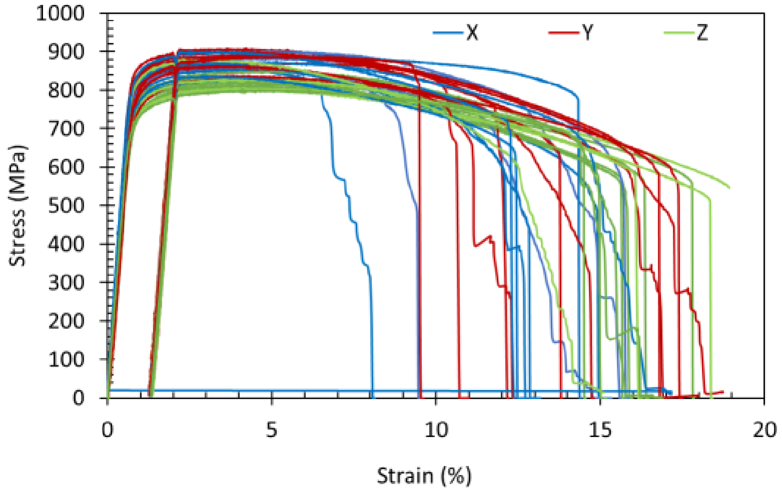


Wrought & As-built Tensile Properties

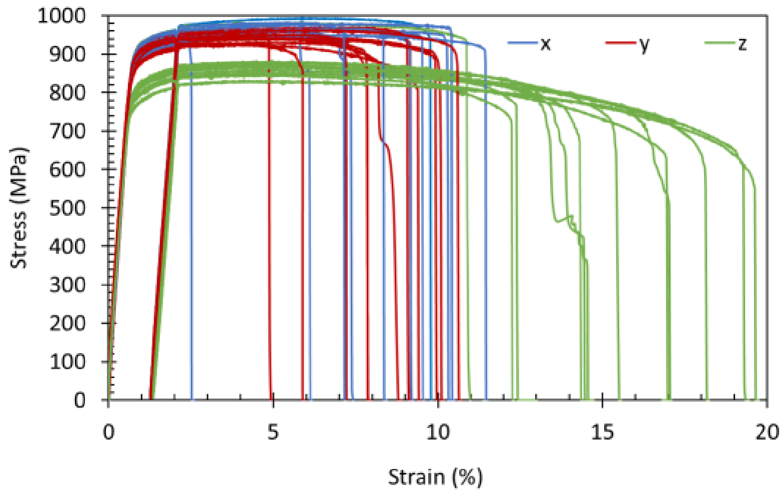
Wrought

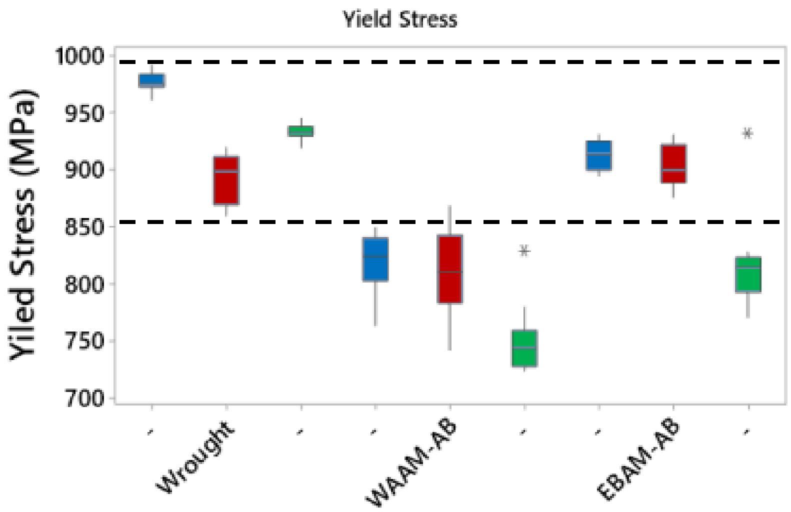


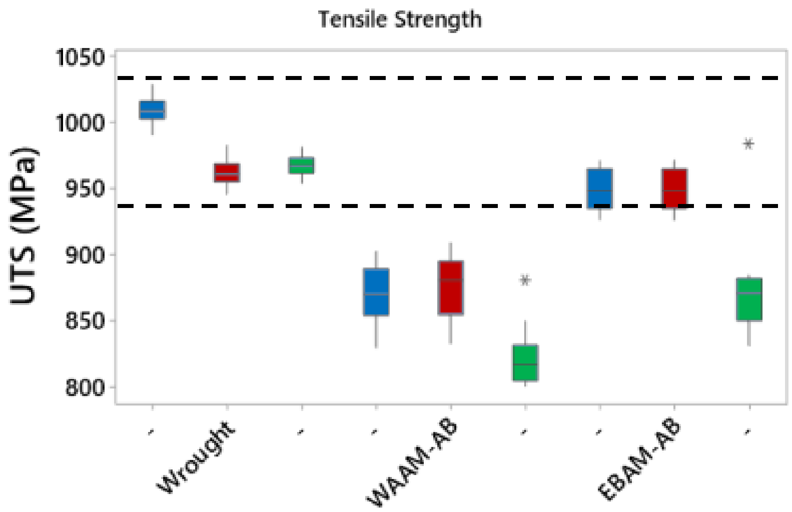
As-built WAAM

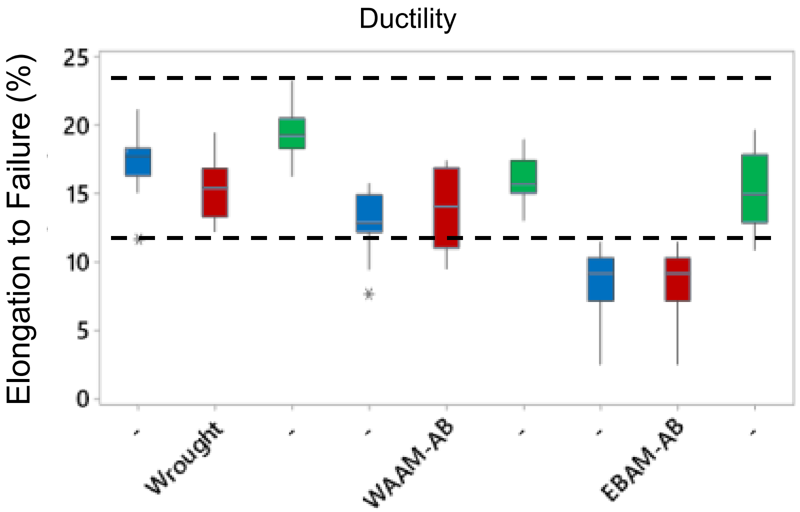


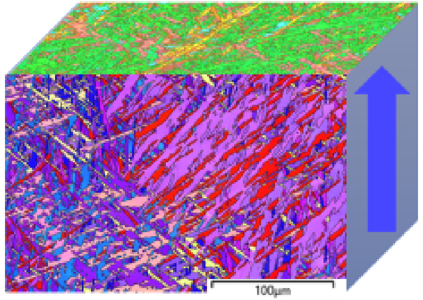
As-built EBAM



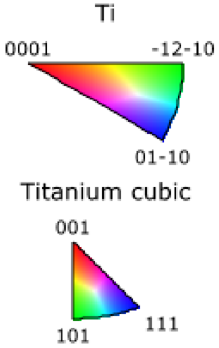








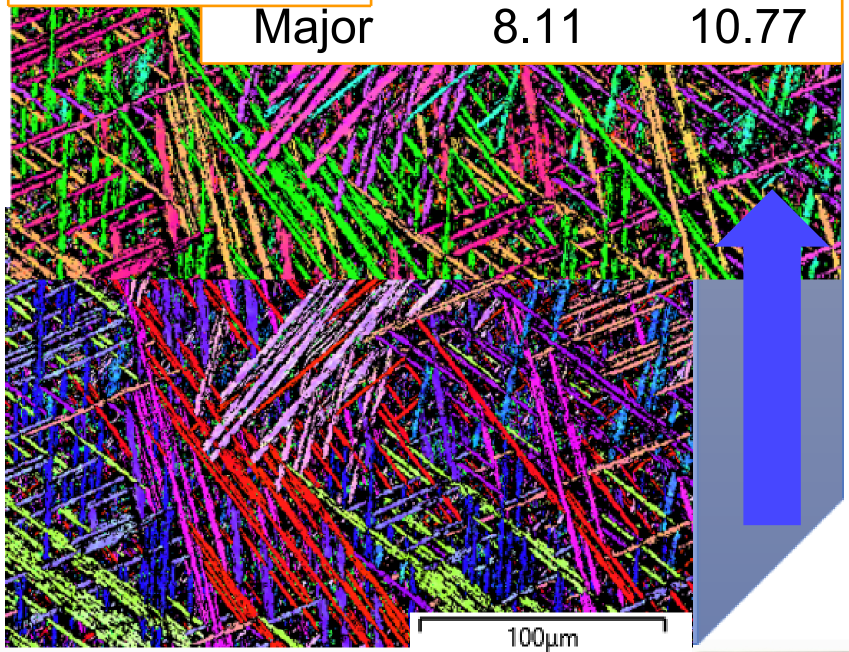
WAAM: Microstructures



HT1: β

Phase	Fraction
Alpha	99%
Beta	< 1%

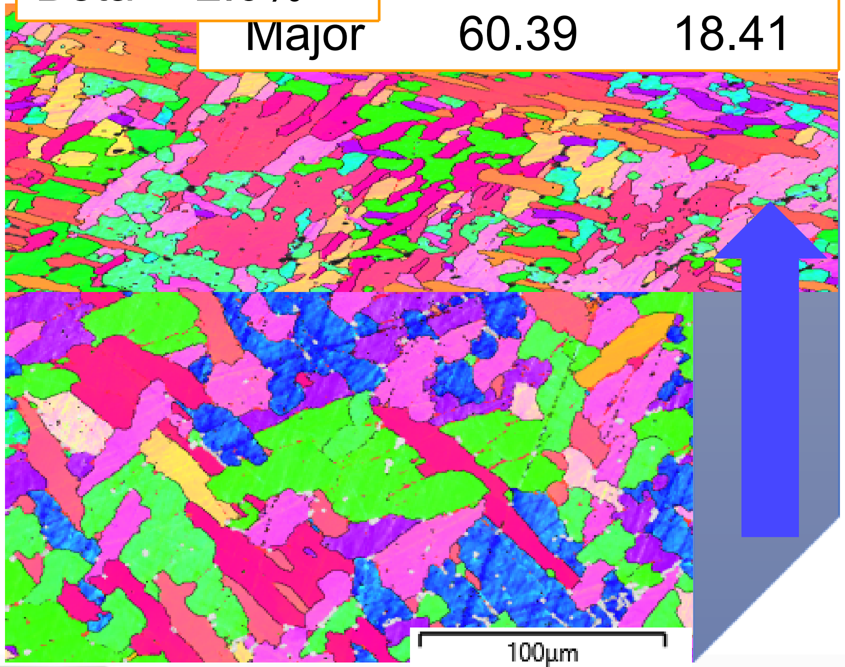
	Average (mm)	Std (mm)
	2.34	1.46
Major	8.11	10.77



HT2: α

Phase	Fraction
Alpha	95.9%
Beta	2.0%

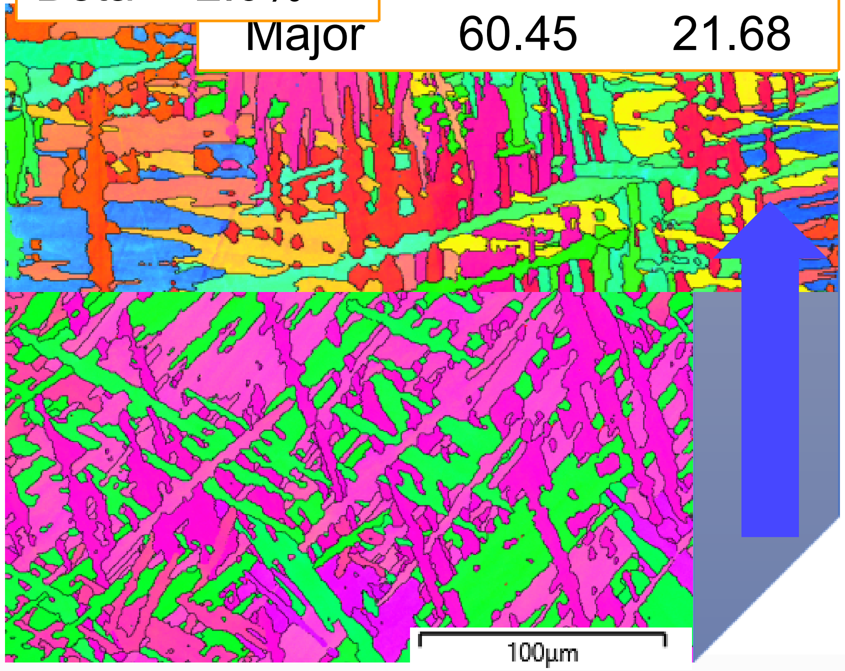
	Average (mm)	Std (mm)
	27.98	9.1
Major	60.39	18.41



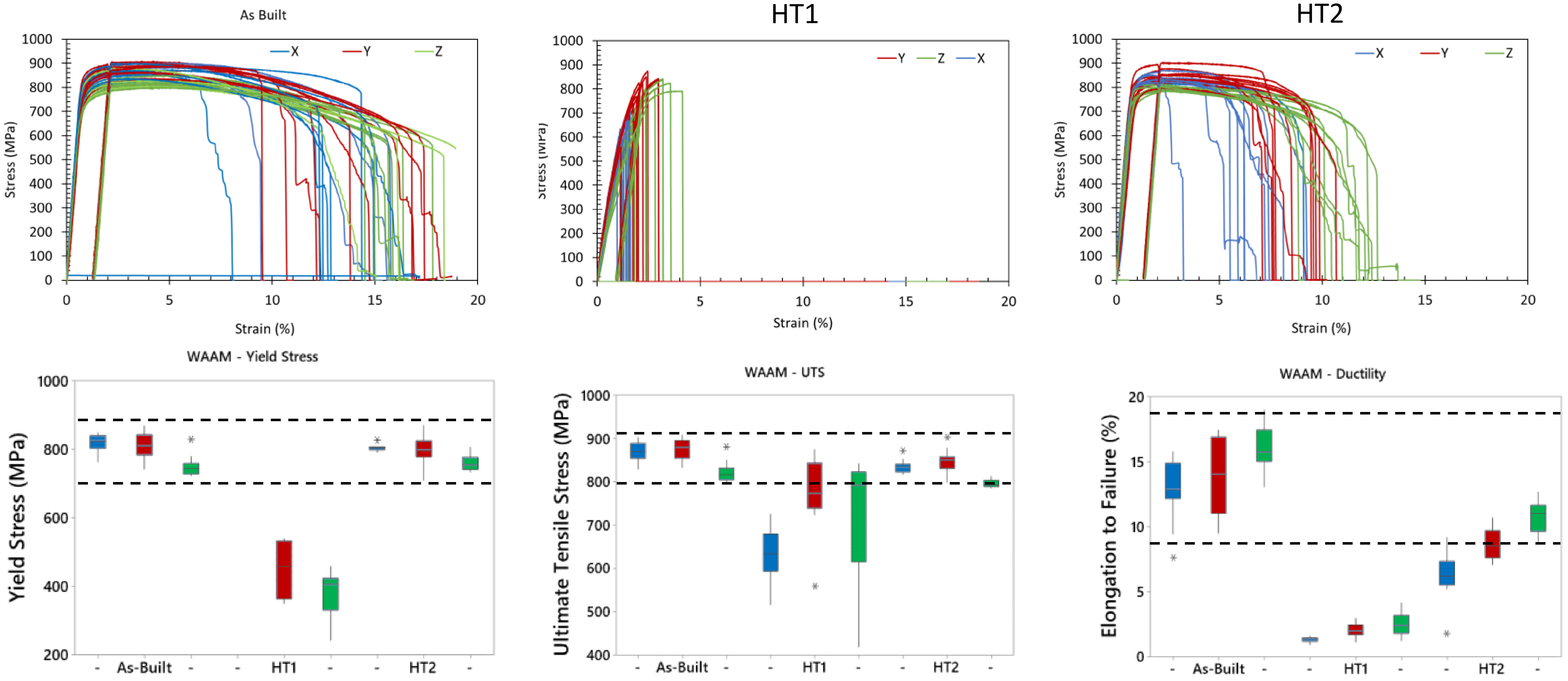
HIP

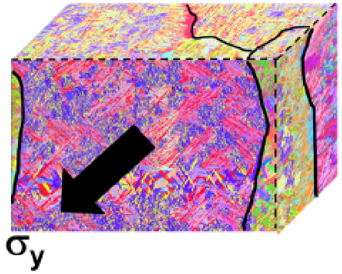
Phase	Fraction
Alpha	95.9%
Beta	2.0%

	Average (mm)	Std (mm)
	24.26	8.11
Major	60.45	21.68



WAAM Tensile Properties





Fractography: WAAM

WAAM-AB

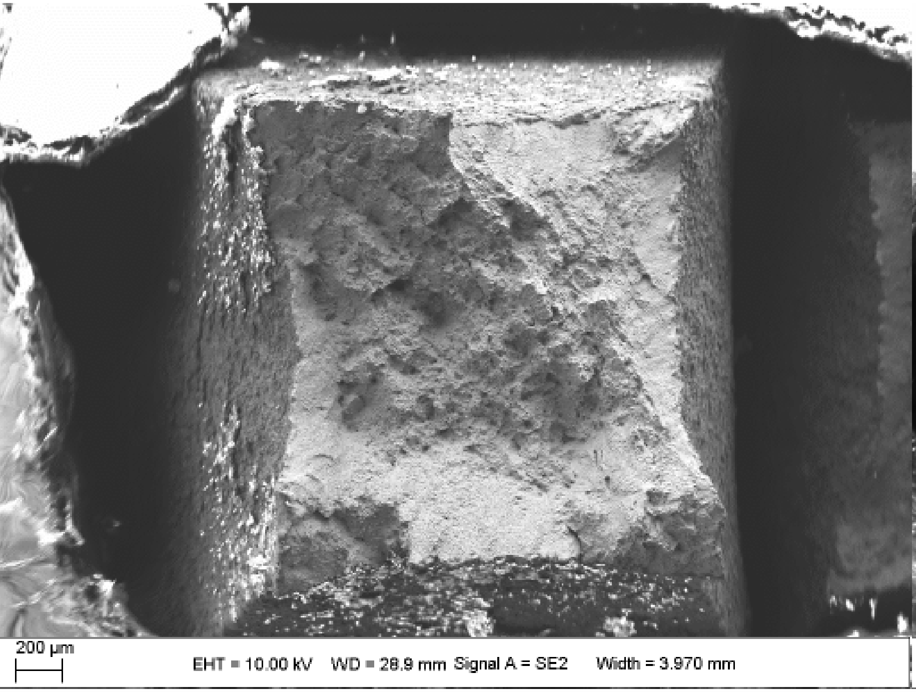
Ductile transcrystalline fracture

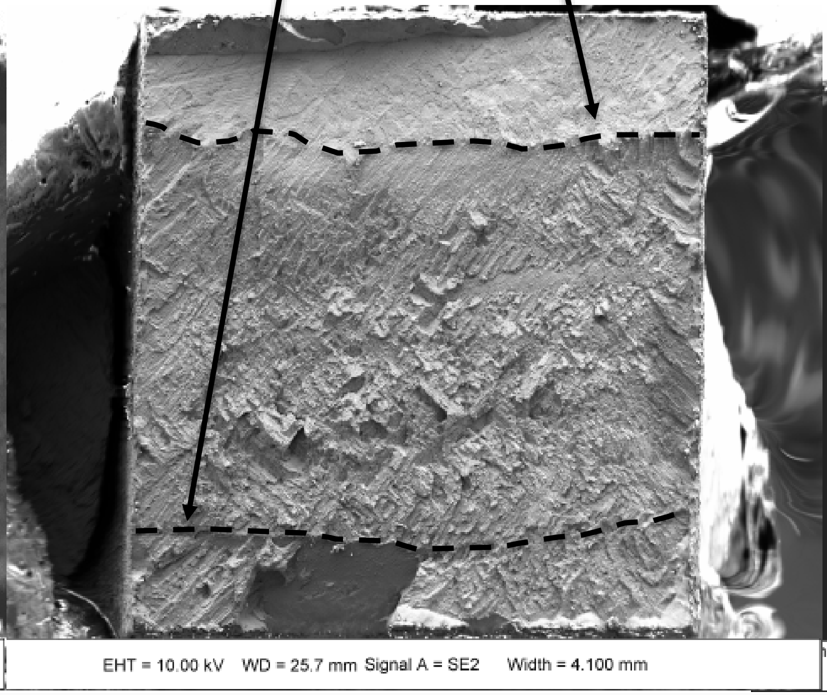
HT1: β

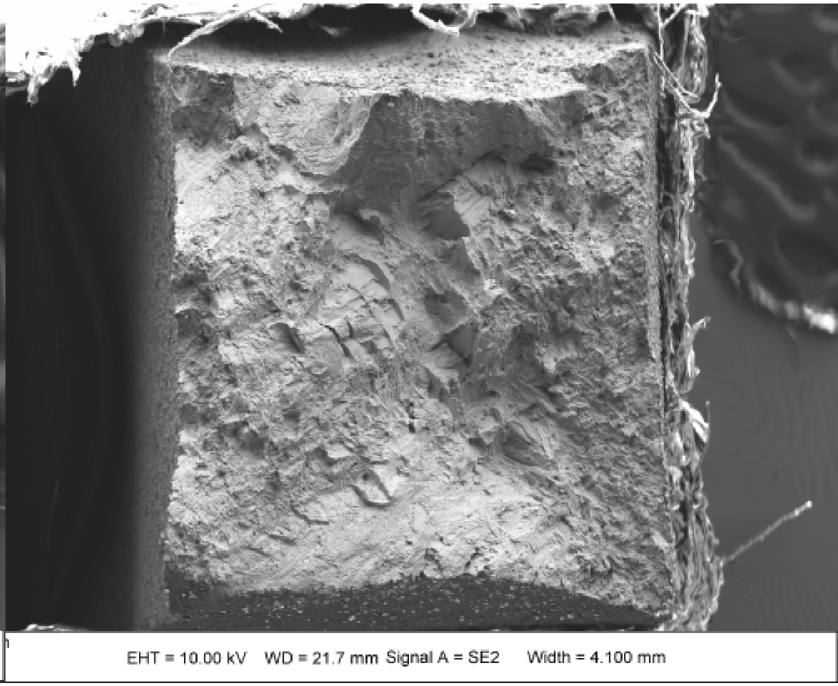
Intercrystalline fracture along continuous α

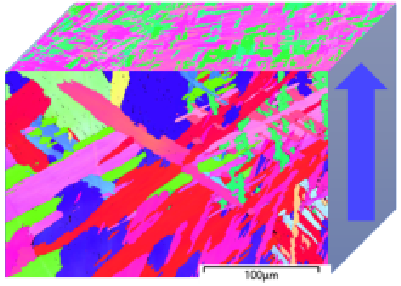
HT2: α

Mix of ductile intercrystalline & transcrystalline fracture

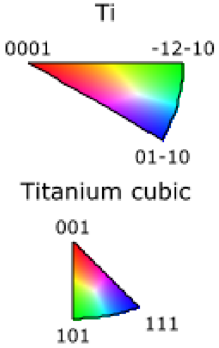








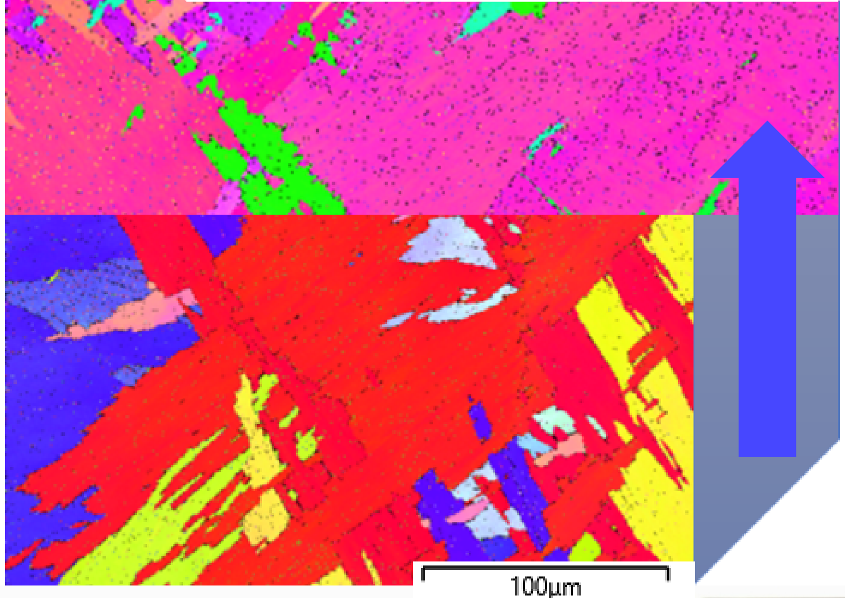
EBAM: Microstructures



HT1: β

Phase	Fraction
Alpha	99%
Beta	< 1%

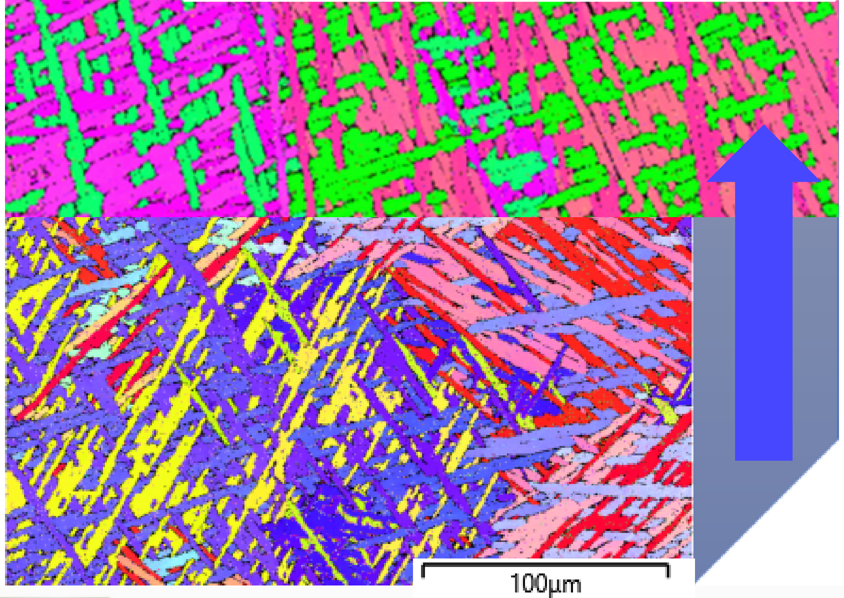
	Average (µm)	Std (µm)
Minor	3.31	0.35
Colony	218.46	30.25



HT2: α

Phase	Fraction
Alpha	98.3%
Beta	1.7%

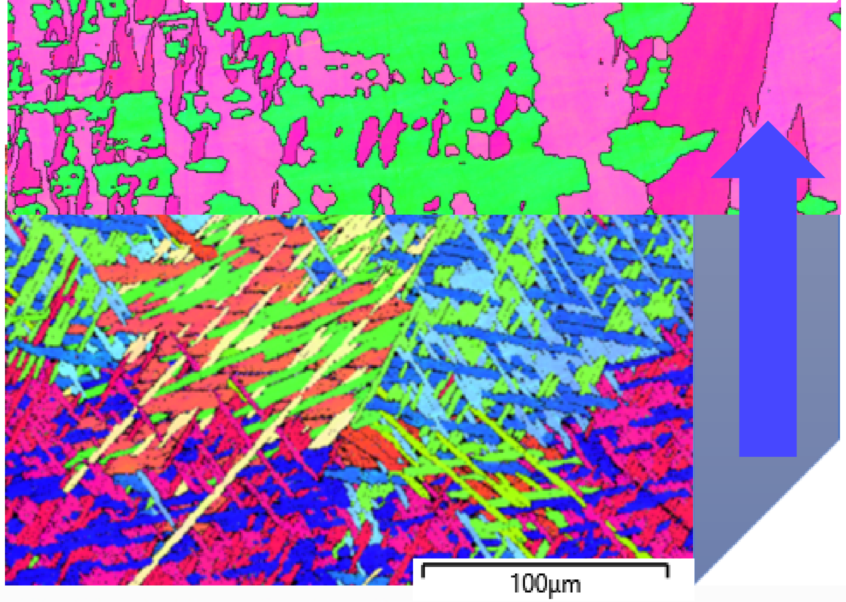
	Average (µm)	Std (µm)
Minor	30.5	6.42
Major	89.74	21.73



HIP

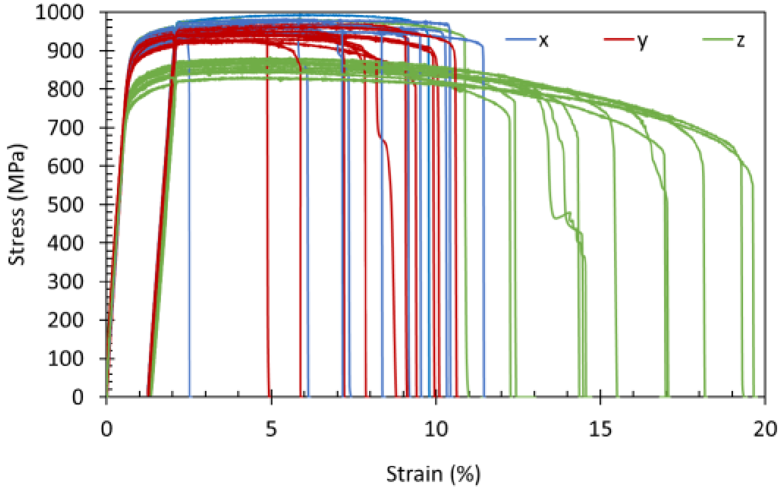
Phase	Fraction
Alpha	87.7%
Beta	0.7%

	Average (µm)	Std (µm)
Minor	39.26	10.54
Major	100.05	29.74

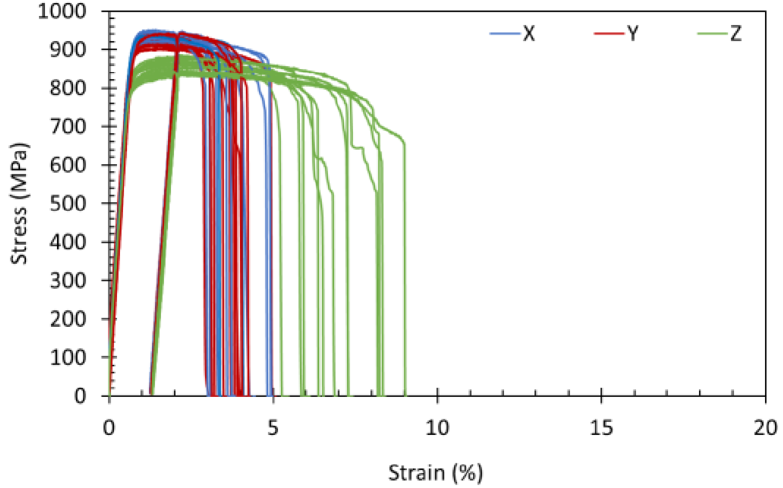


EBAM Tensile Properties

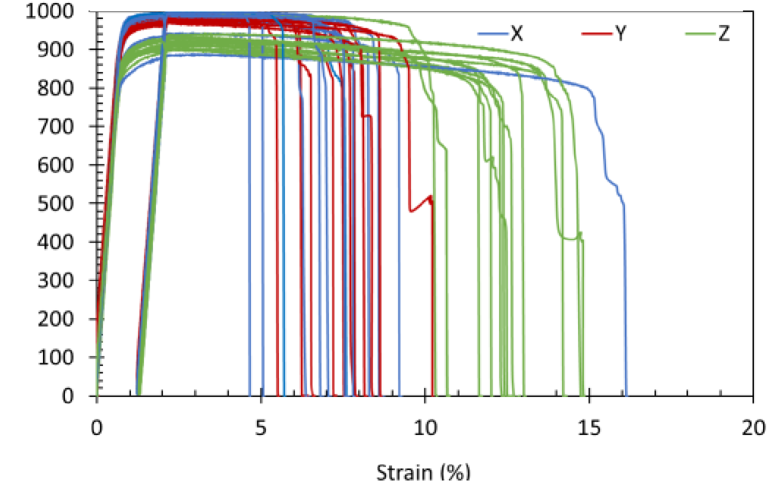
As-built

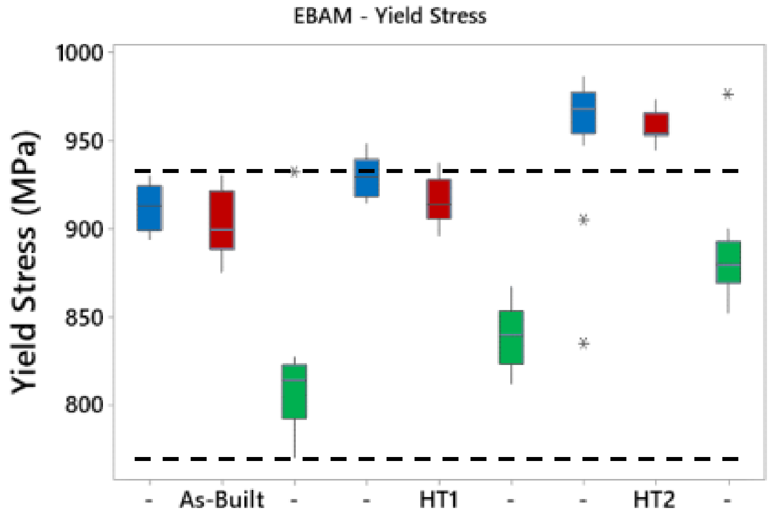


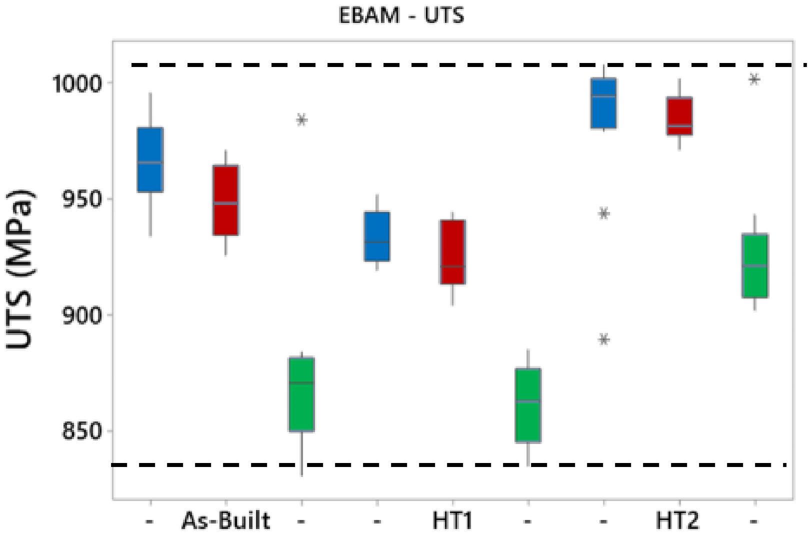
HT1

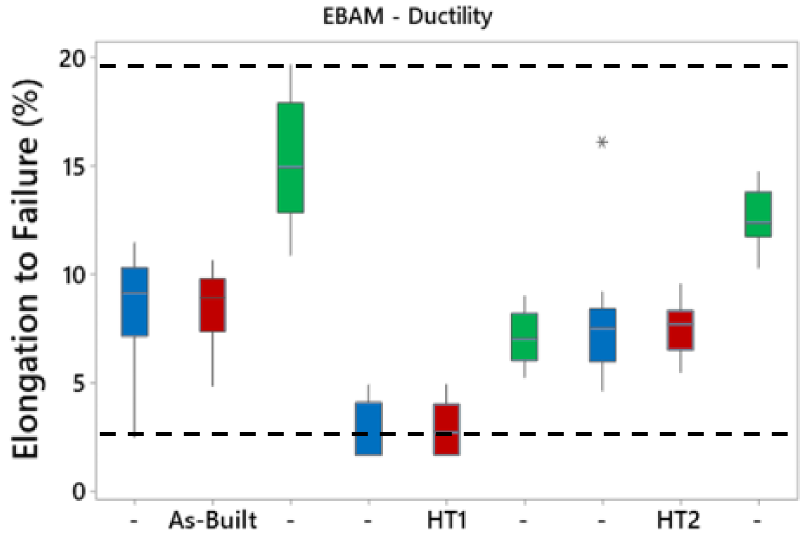


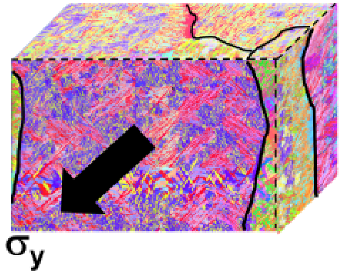
HT2











Fractography: EBAM

EBAM-AB

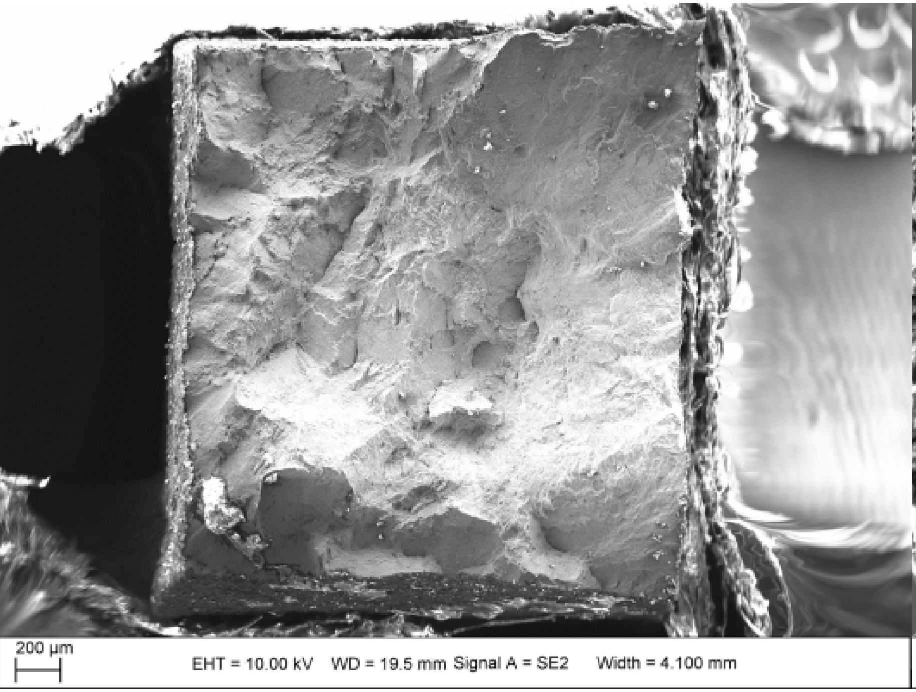
Mix of ductile intercrystalline & transcrystalline fracture

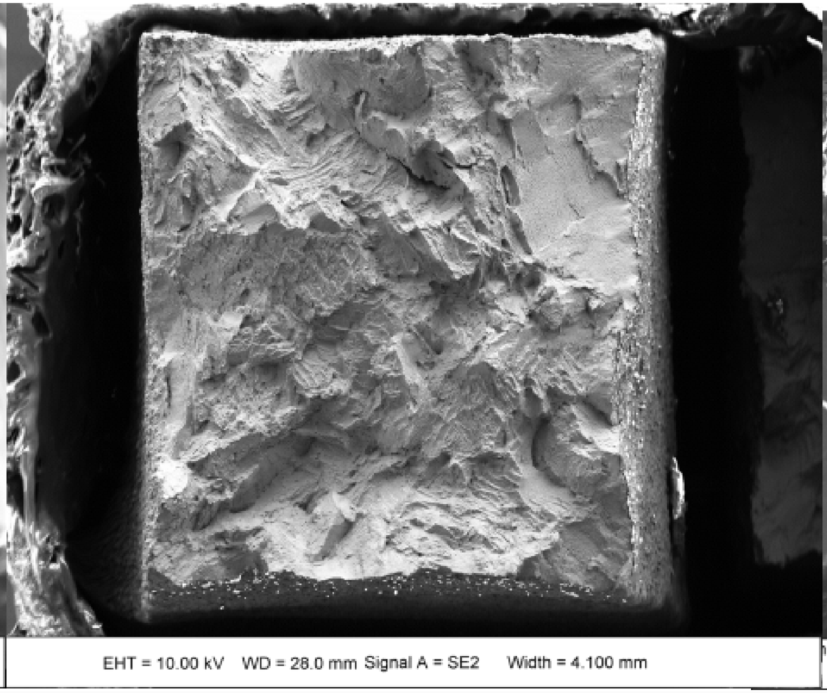
HT1: β

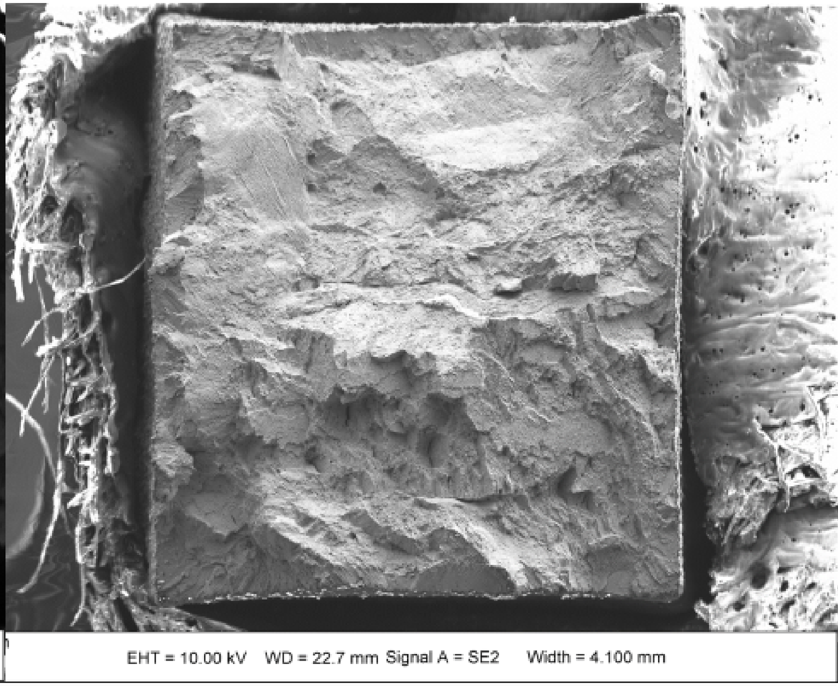
Mix of ductile intercrystalline & transcrystalline fracture

HT2: α

Mix of ductile intercrystalline & transcrystalline fracture



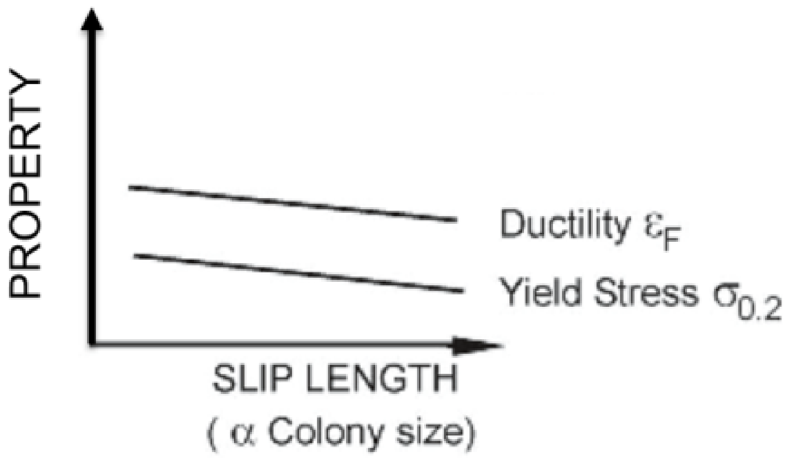




Competing Failure Mechanisms

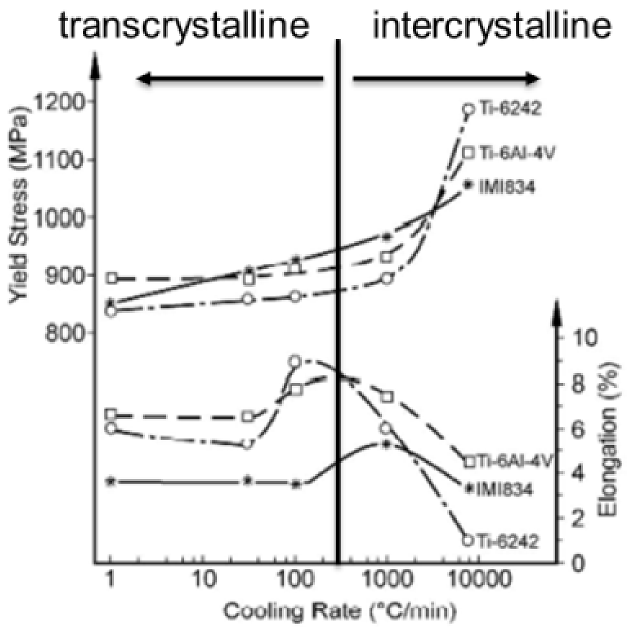
AB, HT1: β

Cooling rates affect the slip length/colony size



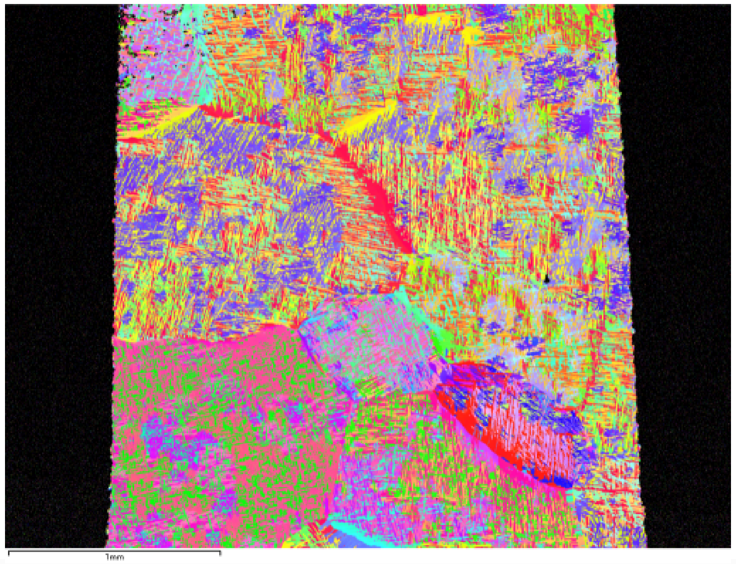
HT1: β

High cooling rate from β field result in intercrystalline facture at prior β



AB, HT2: α

Growth of continuous a at prior b results in lower strength compared to matrix

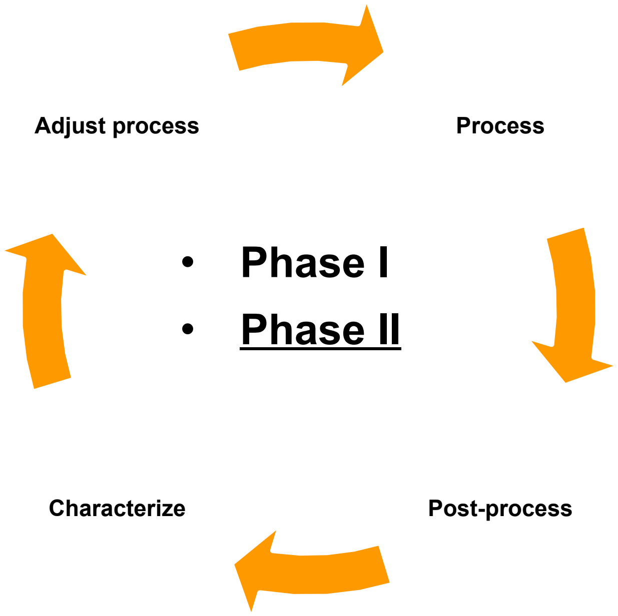


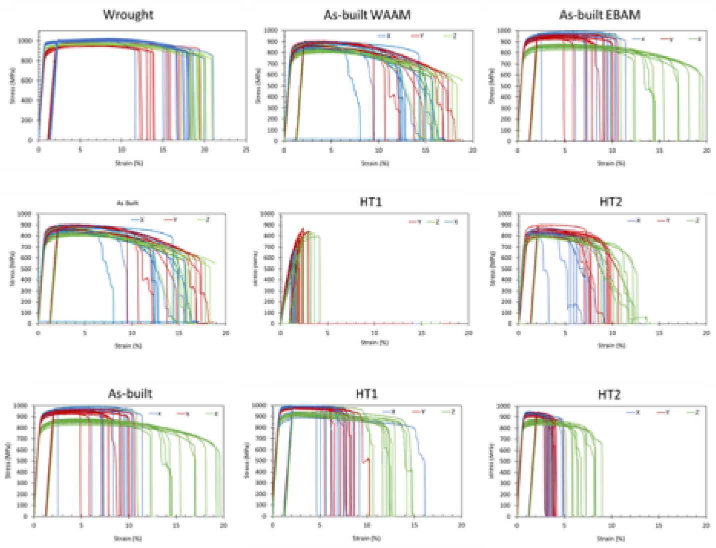
Conclusions/Summary

- β & ($\alpha + \beta$) field heat treatments do not provide convincing benefits to WAAM/EBAM tensile properties
- WAAM showed higher density of defects than EBAM
- Microstructure plays a greater role in failure than defects for both WAAM & EBAM processes
- Lower cooling rates for EBAM resulted in higher density of continuous a along prior-β boundaries and larger degree of anisotropy
- Initial microstructure plays a pivotal role in final grain morphology after heat treatment

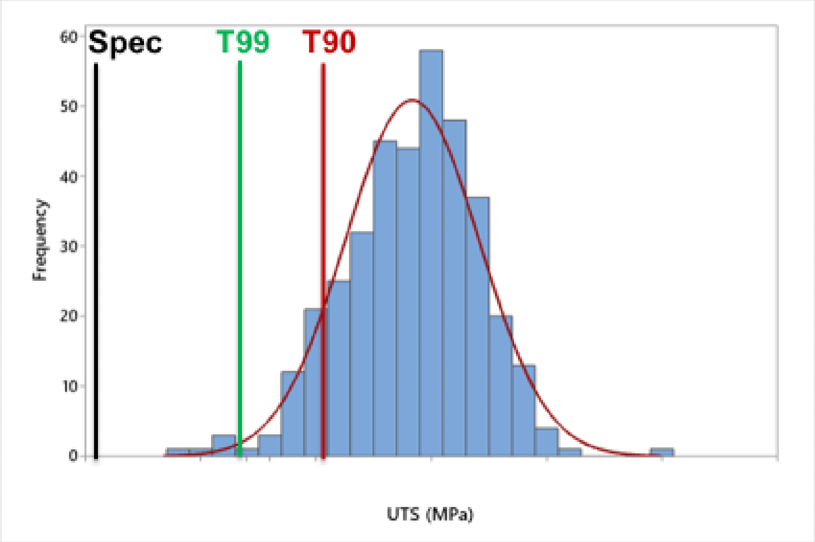
Remaining Effort

- Complete testing on HIP specimens
- Investigate stress relief + Aging heat treatment schedules
- Finalize heat treatment schedule for bulk tensile testing





Standard E8 Testing



Thank You!

Jonathan Pegues, Sandia National Laboratories (SNL)

jwpegue@sandia.gov

- **Acknowledgements:** Luis Jauregui, John Williard, Priya Pathare, Jay Carroll, Christina Profazi, Johnathon Brehm, Jeier Yang, Dennis De Smet, Chuck Walker, Elliott Fowler, Elizabeth Huffman

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy National Nuclear Security Administration under contract DE-NA0003525

Sandia National Laboratories

Colony vs Lamellar