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

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Solid FreeForm Fabrication Symposium

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U.S. DEPARTMENT OF ENERGY

NNSA

Additive Manufacturing at SNL

Sandia telescope

Printed battery

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”

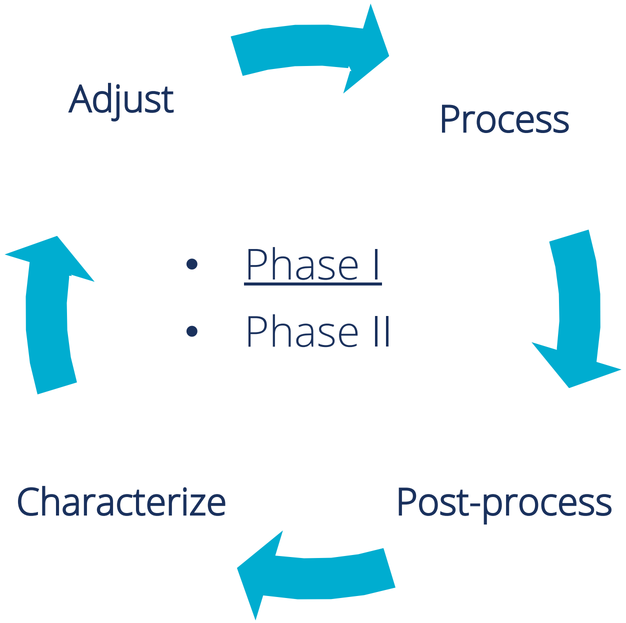
Continually growing interest across Sandia missions

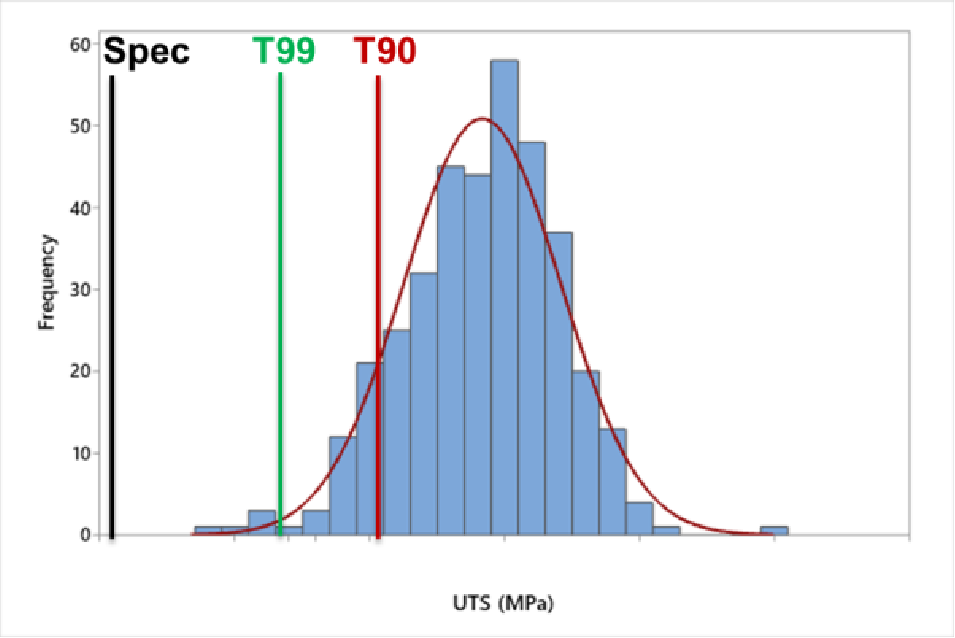
Full scale additive weapon mock-up

W-DED: Background

Objective: Provide statistically validated 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





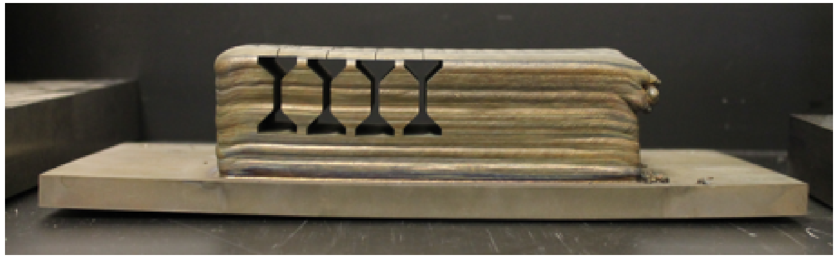
Additive Manufacturing: W-DED

EBAM: Sciaky

Advantages of EBAM:

- High deposition rates
- Low Material waste
- Minimal contamination
- Low feedstock storage requirements

Billet



Pre-form

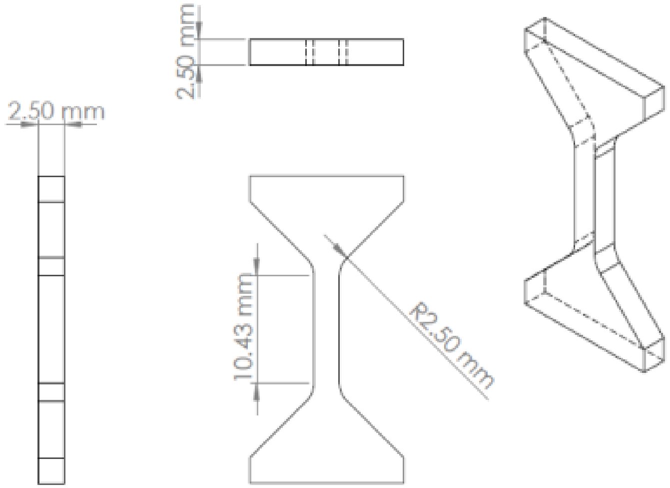
Machined

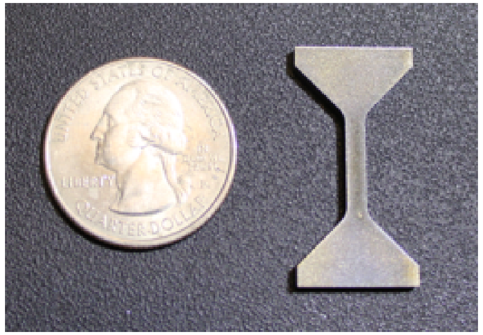
High Throughput Testing

MTS: 858 5-kip frame

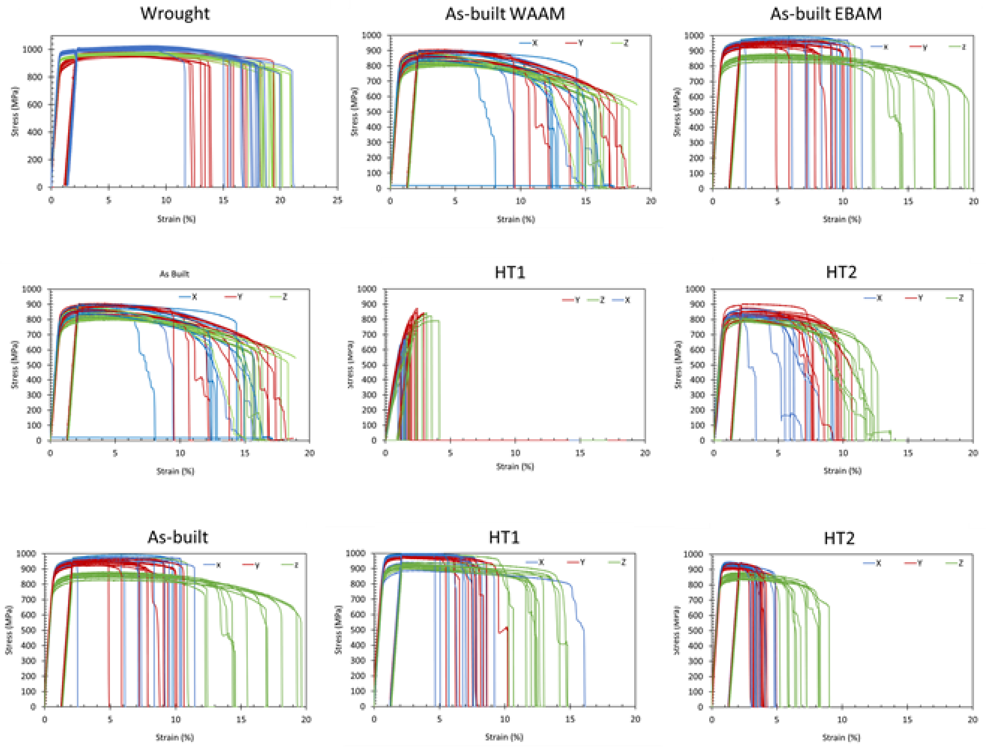
- Displacement rate 0.01 mm/s
- FLIR 90 fps, 4.1 Mpix camera

High Throughput Specimen Geometry

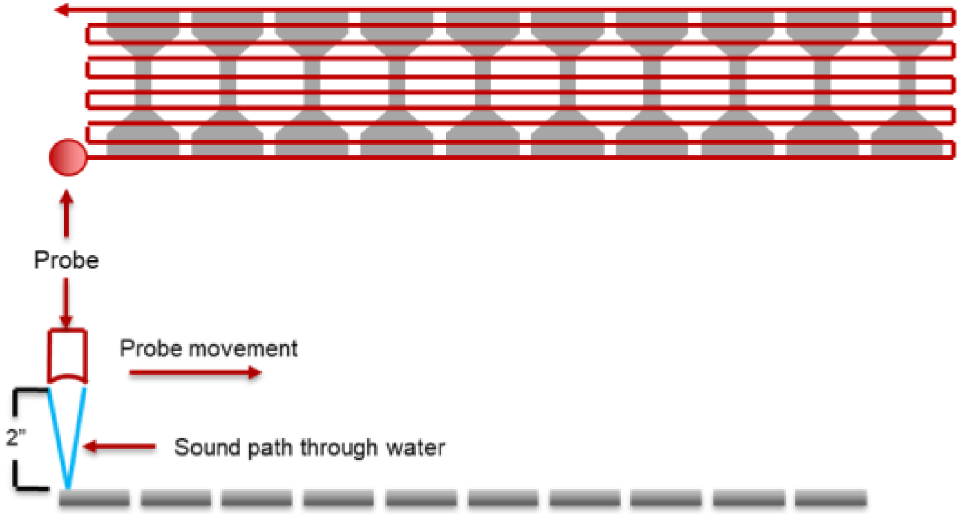


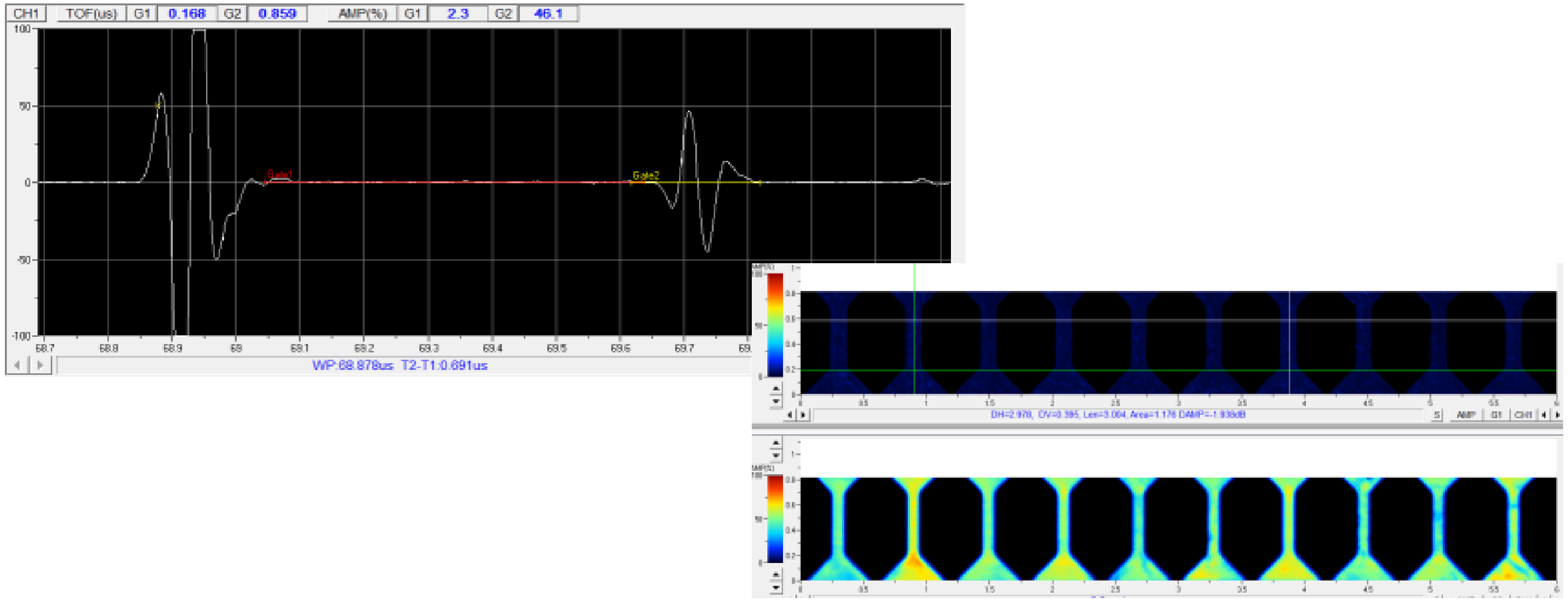


Rapid development of statistically relevant tensile data



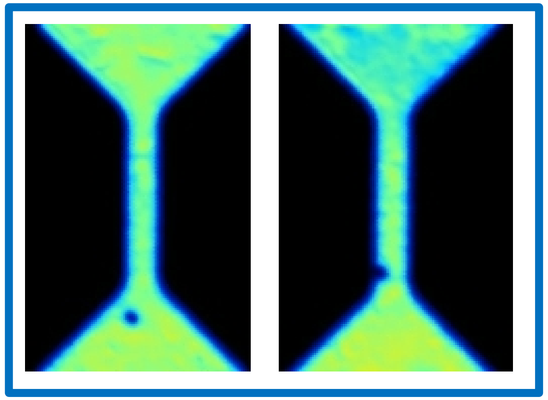
Immersion Ultrasonic Inspection



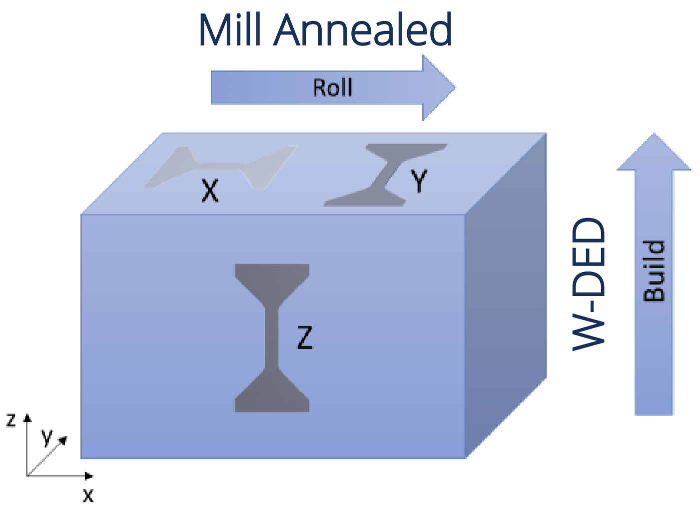


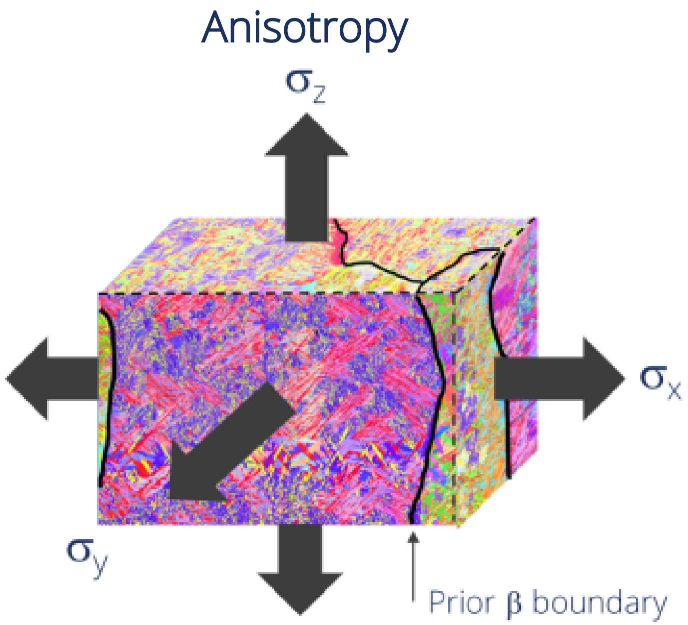
- Immersion inspections were performed from the etched surface.
- ~50 μm resolution and at a height of 50 mm above side being scanned
- No observable defects discovered for wrought material
- Low porosity observed for EBAM 2:164

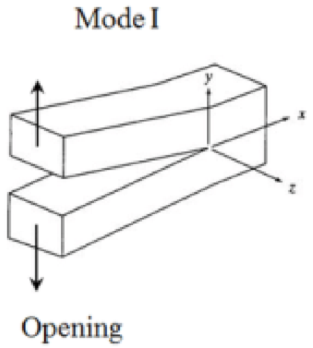
EBAM

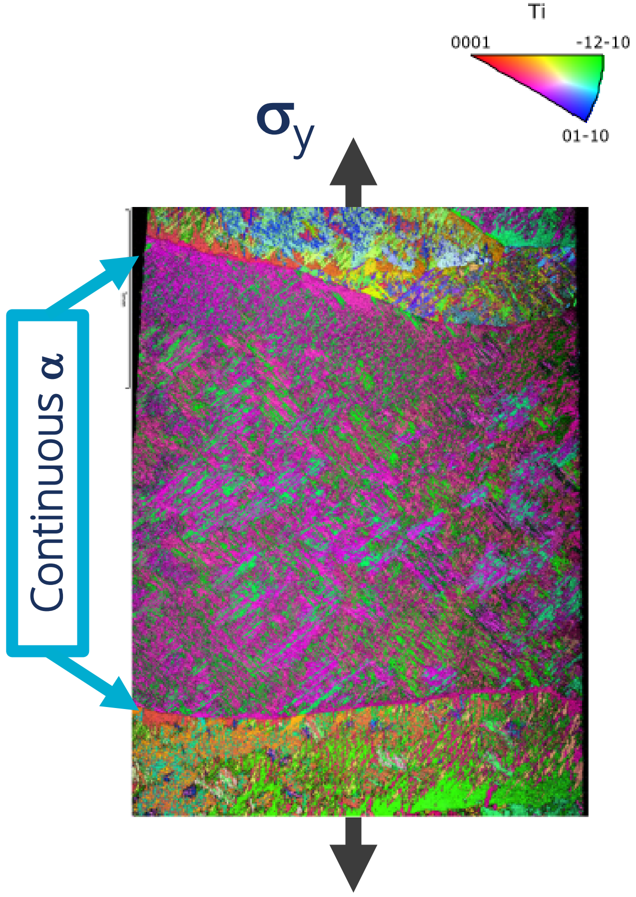


Anisotropy in W-DED Ti-6Al-4V







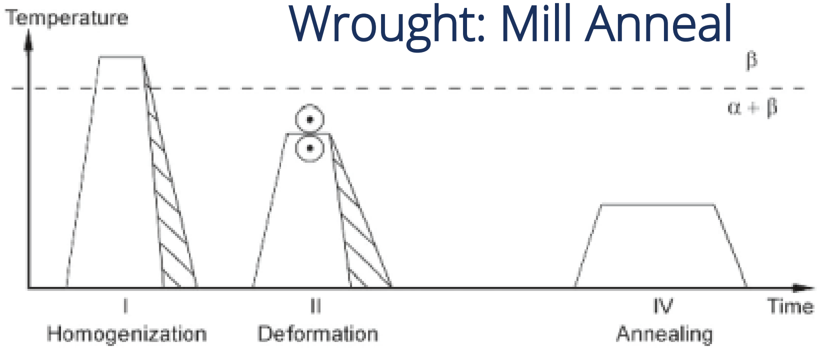


Conventional vs. Additive Manufactured

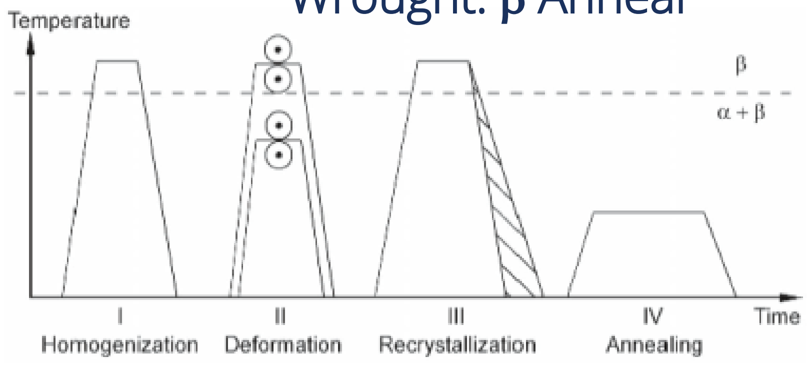
Conventional Process
- Material formed from bulk feedstock
- Microstructure formed prior to geometry
- Well documented post-process effects and properties

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

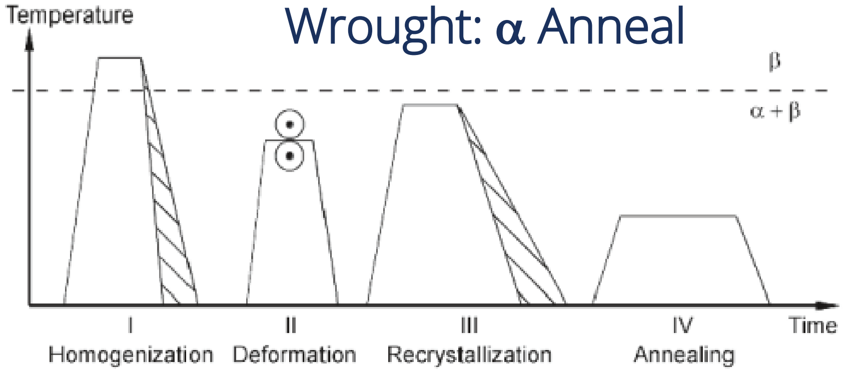
Wrought: Mill Anneal

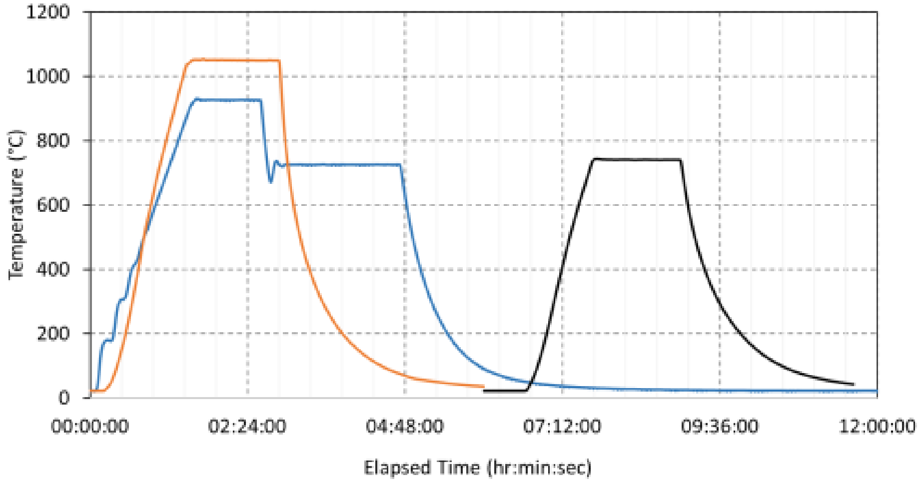


Wrought: β Anneal



Wrought: α Anneal

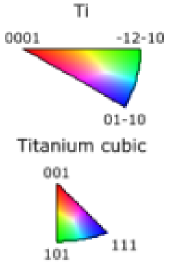




HT1: Beta anneal + Overage
- 1050°C: 1 hour soak
- 725°C: 2 hour soak
- Argon Quench

HT2: Alpha anneal + Overage
- 926°C: 1 hour soak
- 725°C: 2 hour soak
- Argon Quench

Wrought & As-built Microstructures

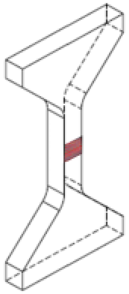


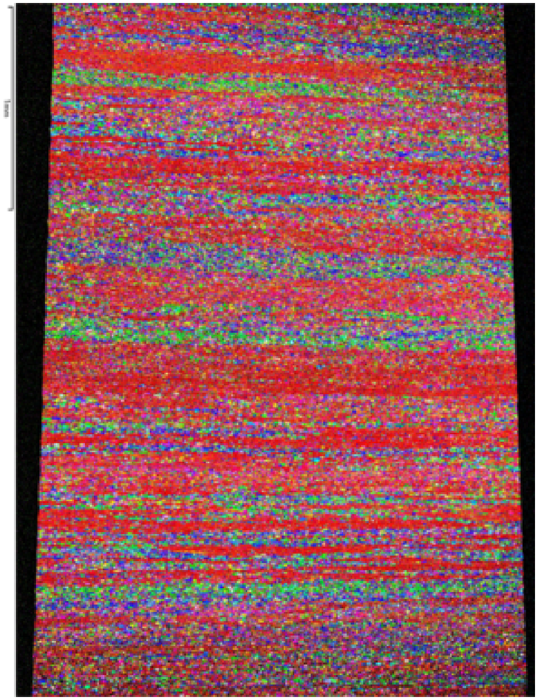
Wrought

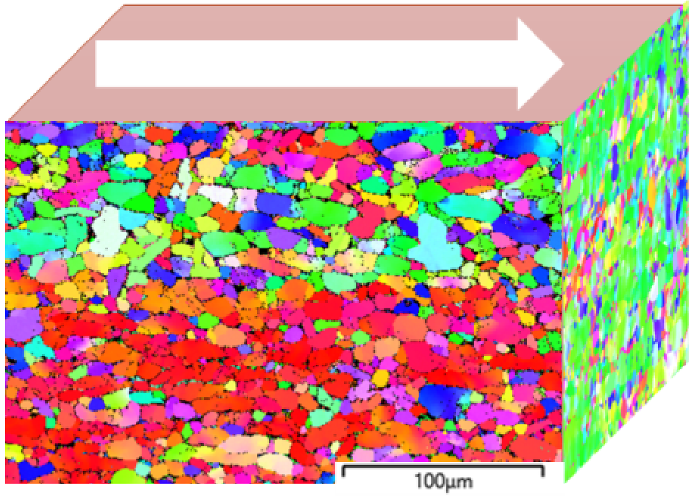
El.	At. %
Al	6.84
V	3.77
Fe	0.14

Phase	Fract.
Alpha	93.4 %
Beta	6.5 %

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





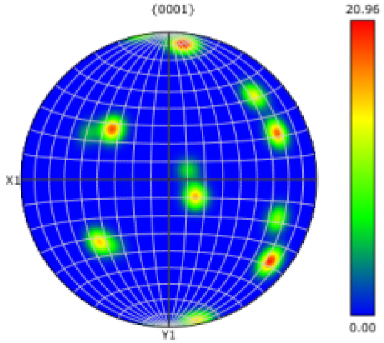


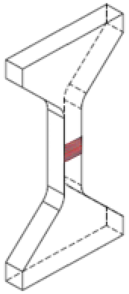
EBAM

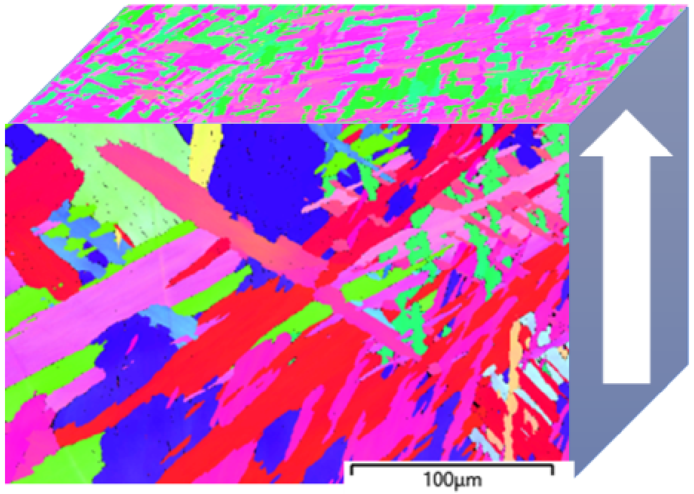
El.	At. %
Al	6.78
V	3.74
Fe	0.23

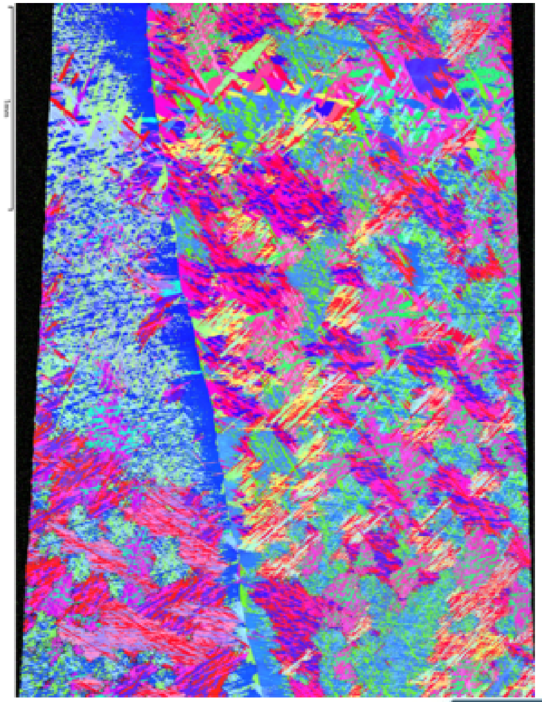
Phase	Fract.
Alpha	99 %
Beta	<1 %

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

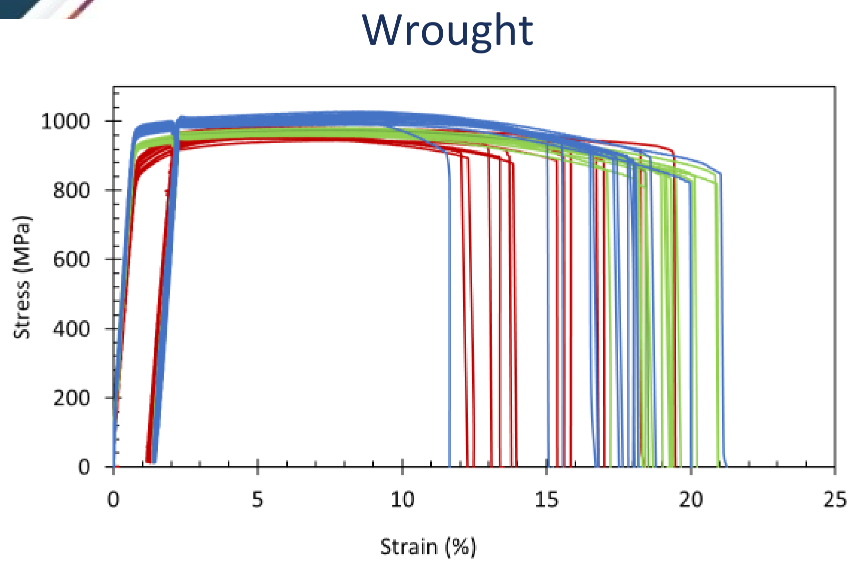


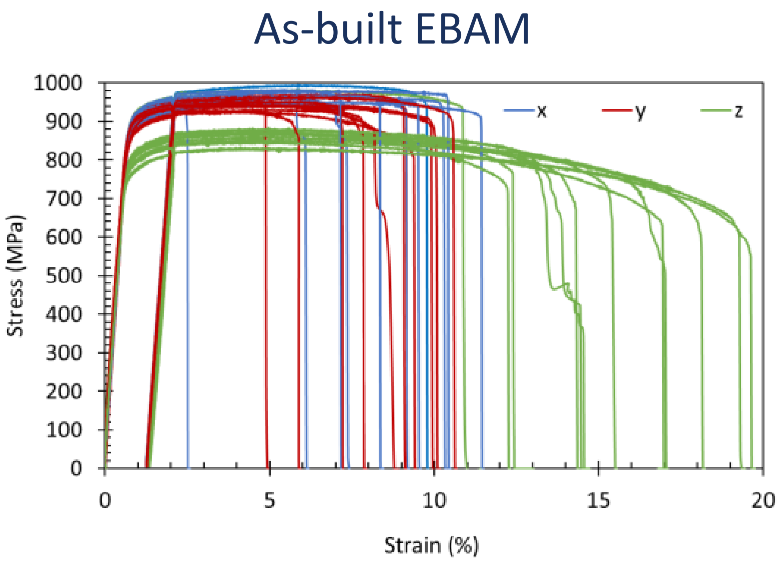


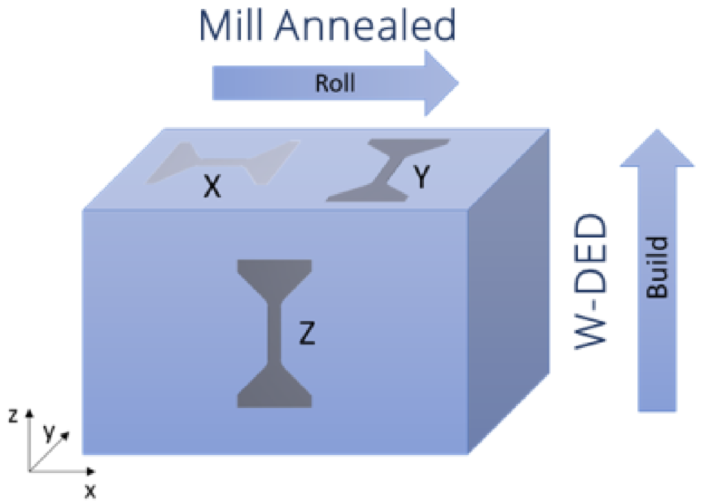


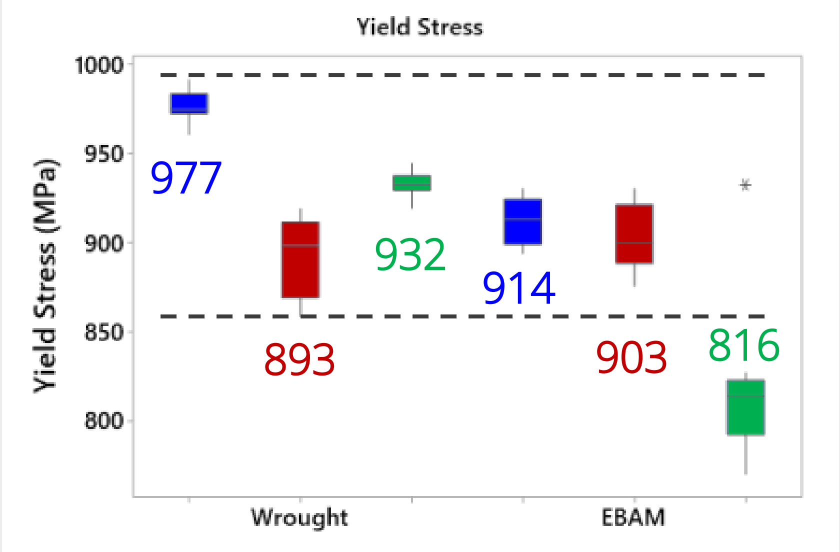


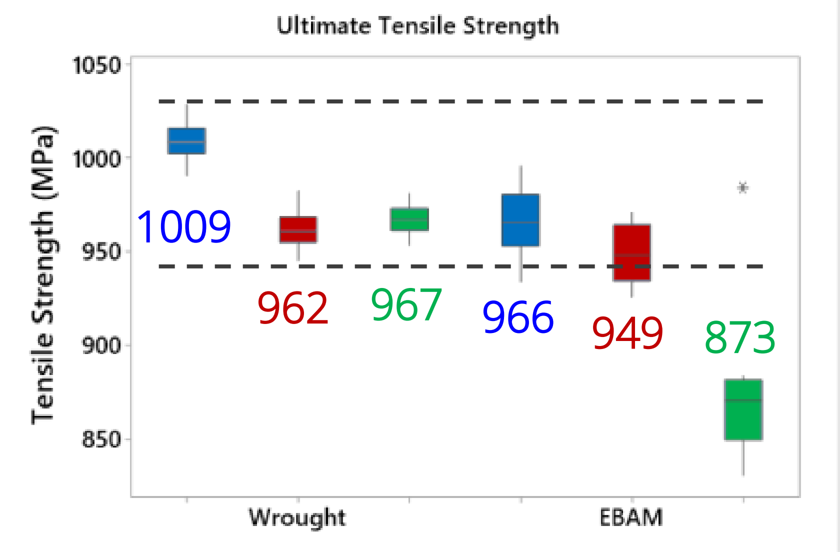
Wrought & As-built Tensile Properties

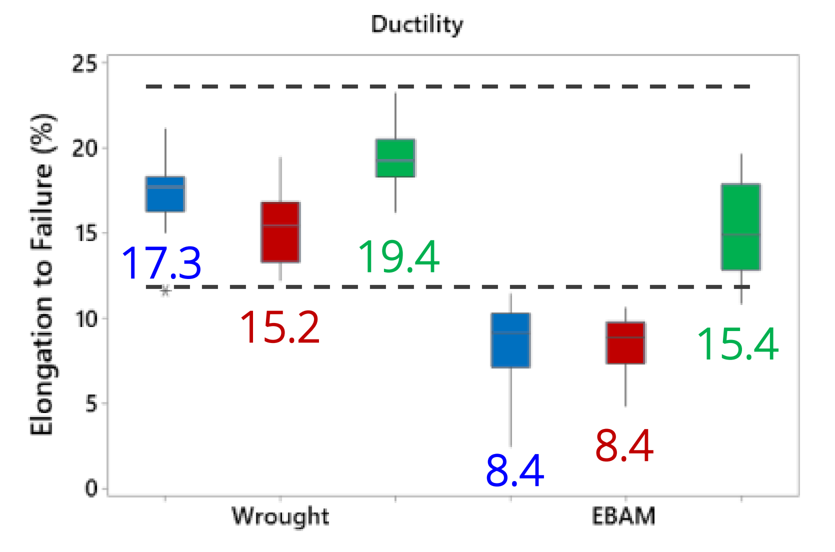






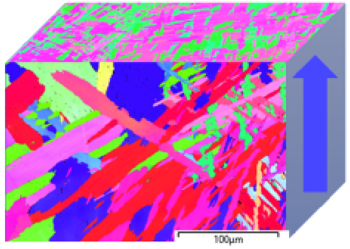


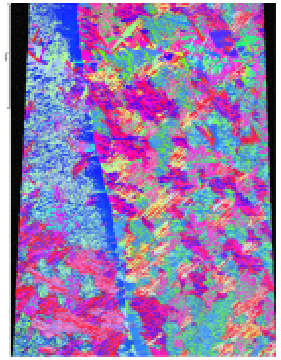


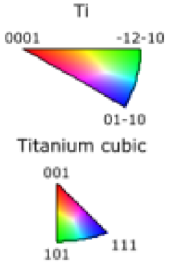


EBAM: Microstructures

As-built



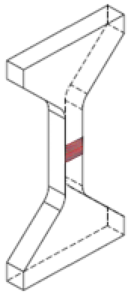


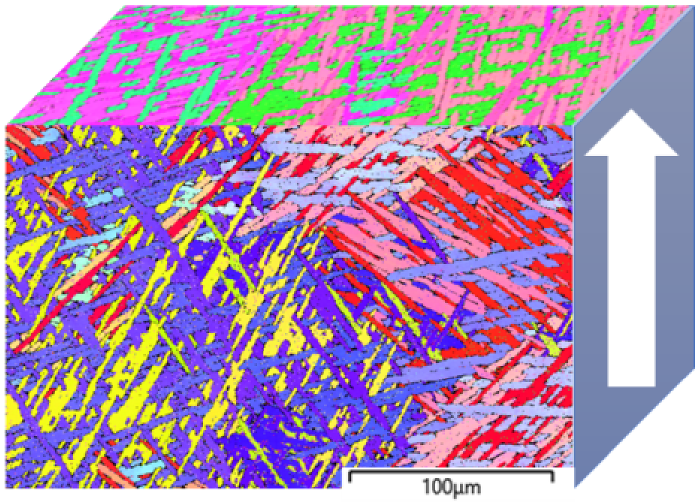


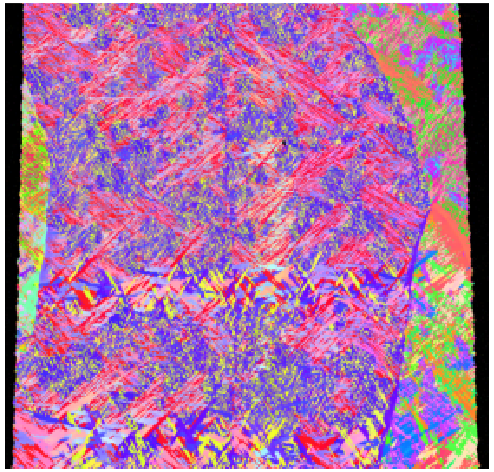
HT1: Beta anneal + Overage

Phase	Fraction
Alpha	98.3%
Beta	1.7%

	Average (µm)	Std (µm)
Minor	3.4	6.42
Major	10.35	21.73



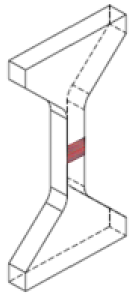


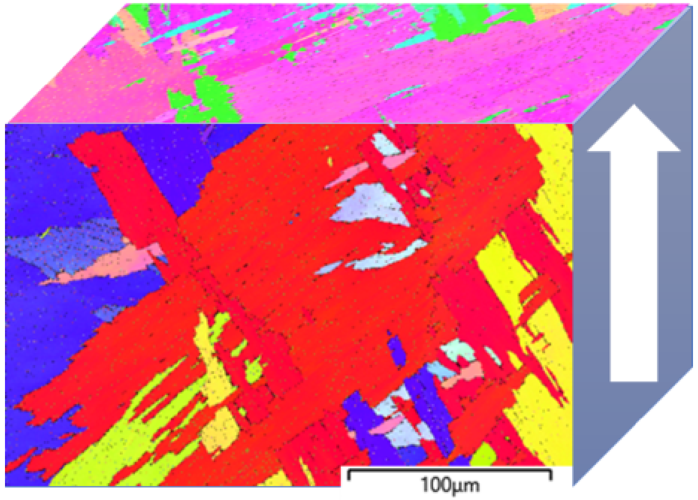


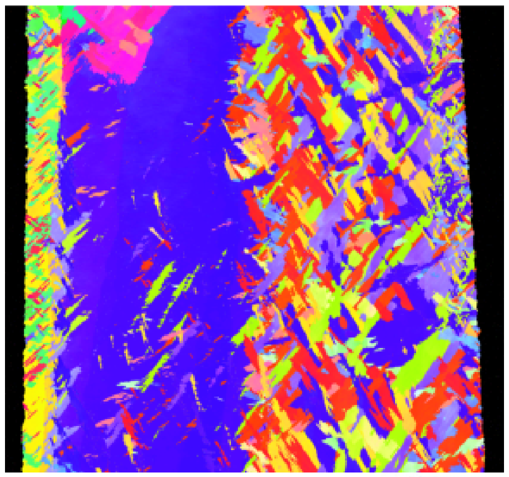
HT2: Alpha anneal + Overage

Phase	Fraction
Alpha	99%
Beta	< 1%

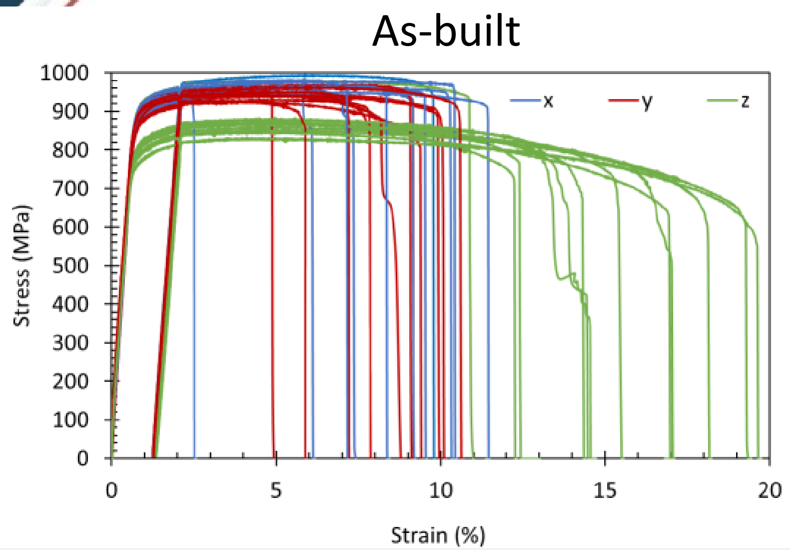
	Average (µm)	Std (µm)
Minor	3.31	0.35
Colony	218.46	30.25

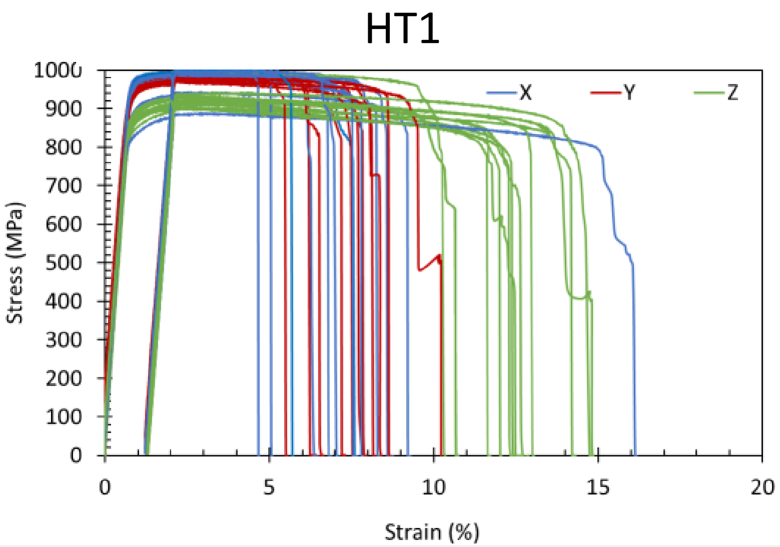


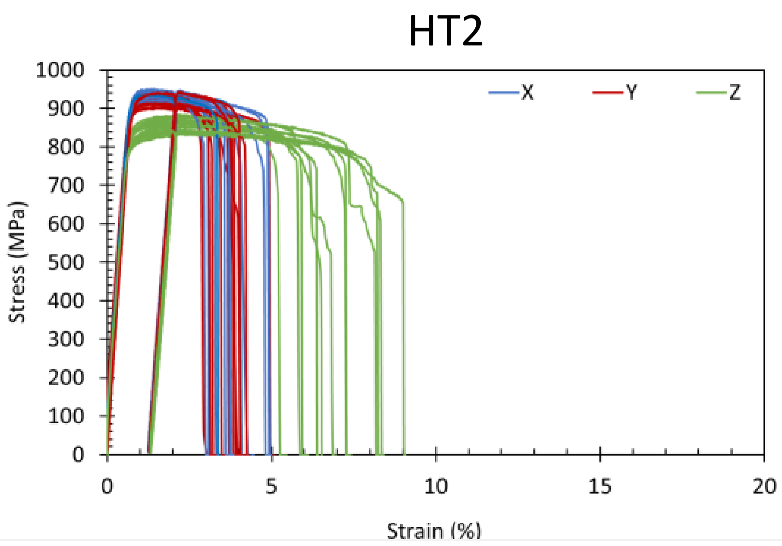


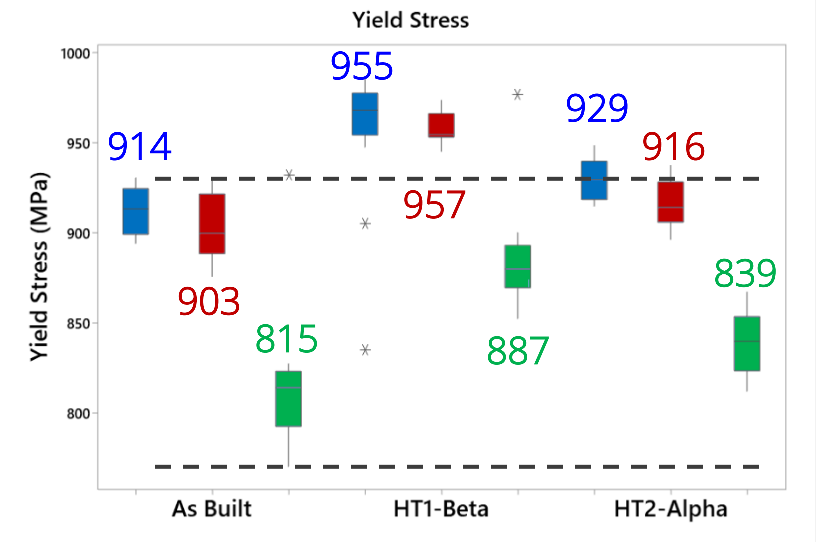


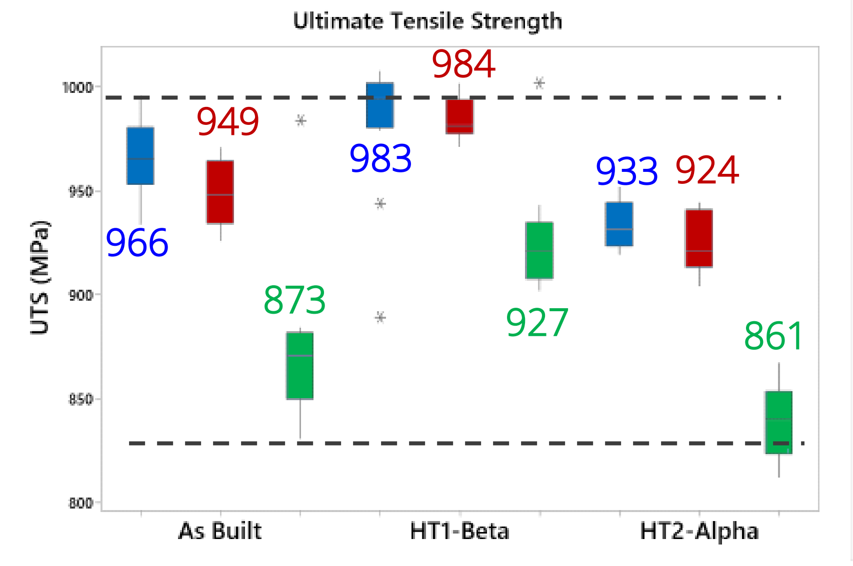
EBAM Tensile Properties

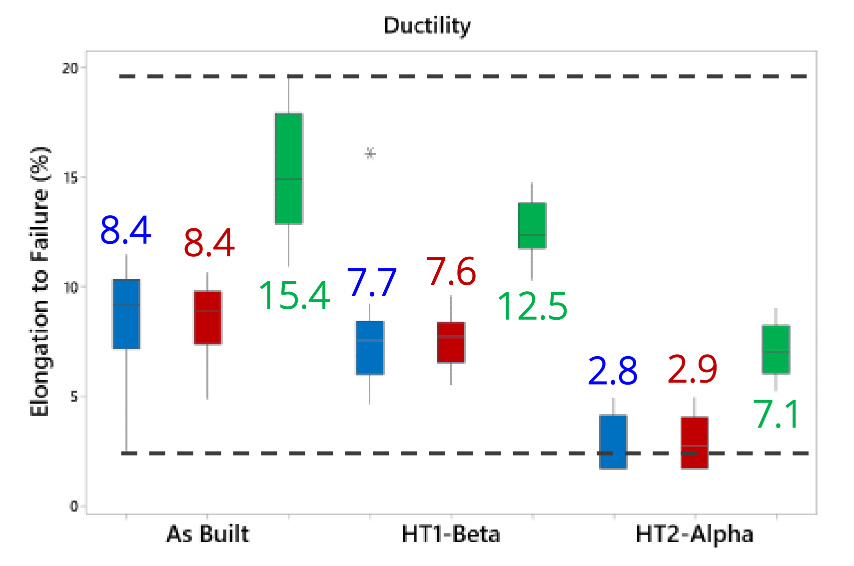




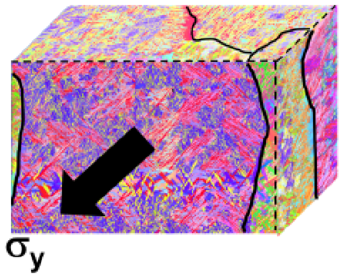








Fractography: EBAM



EBAM-AB

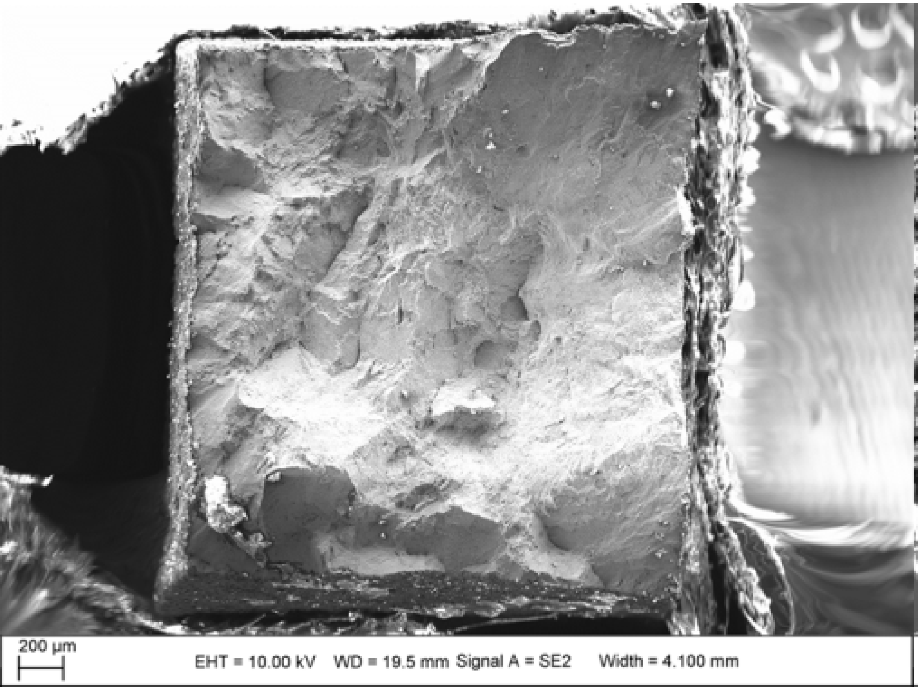
Mix of ductile intercrystalline & transcrystalline fracture

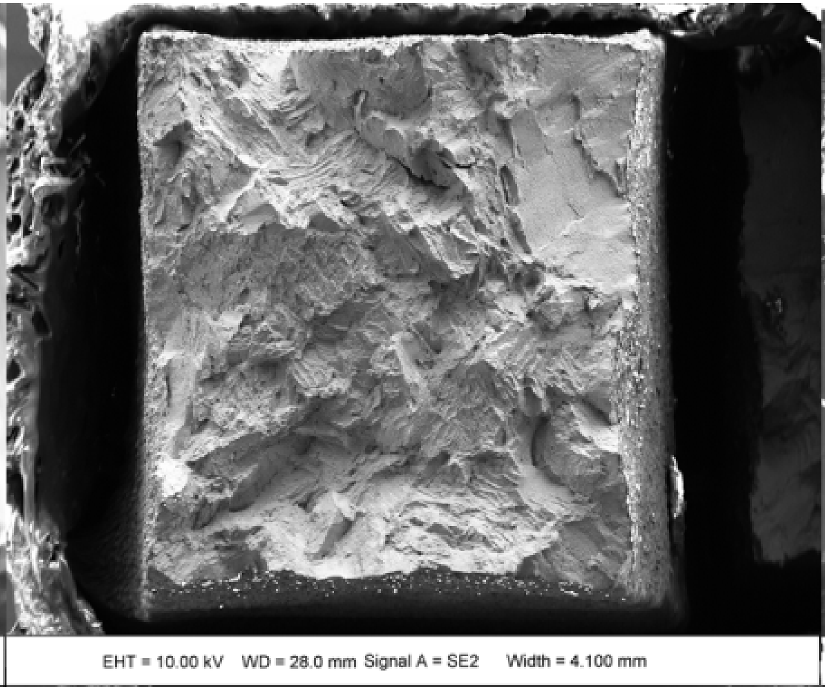
HT1: β

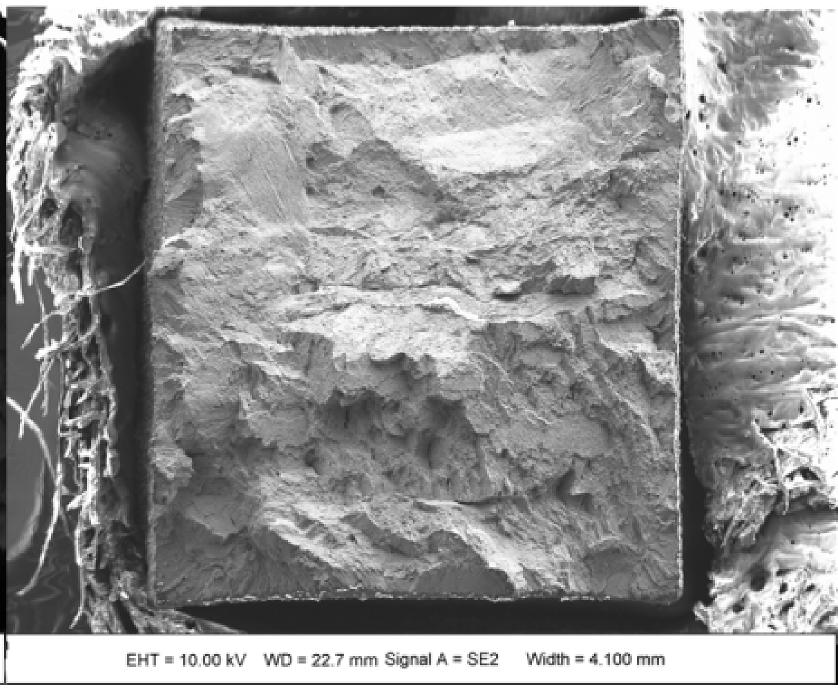
Mix of ductile intercrystalline & transcrystalline fracture

HT2: α

Mix of ductile intercrystalline & transcrystalline fracture



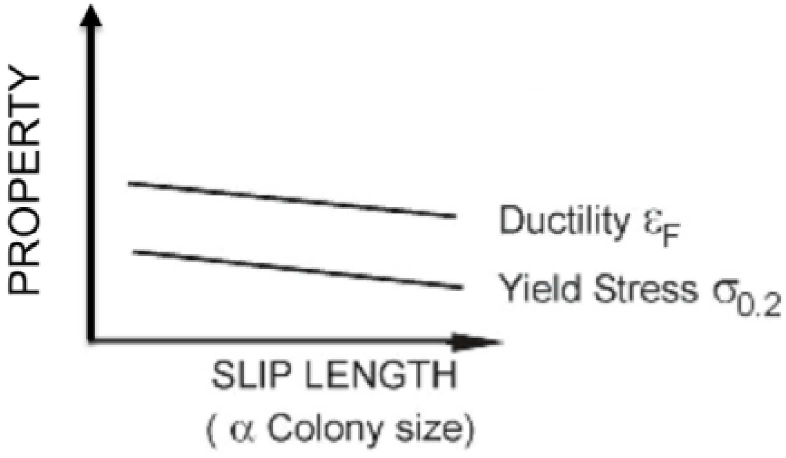


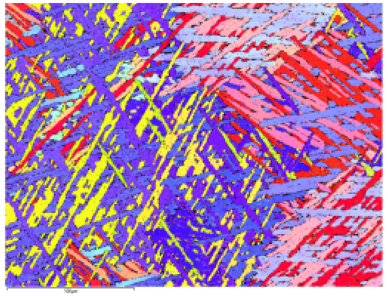


Competing Failure Mechanisms

AB, HT1: β, HT2: α

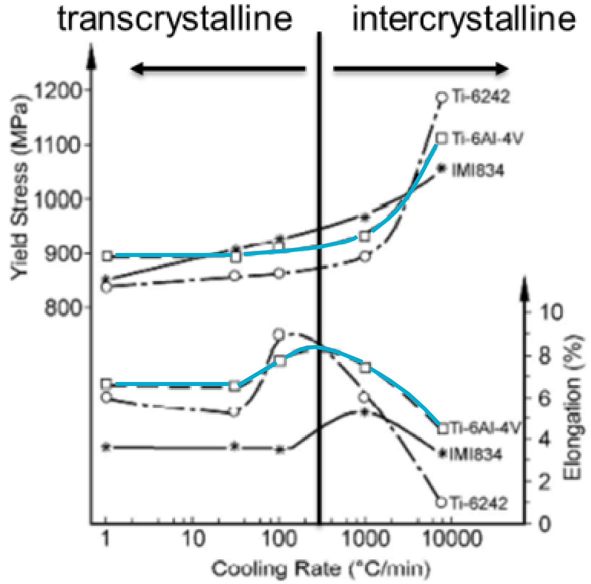
Cooling rates affect the slip length/colony size

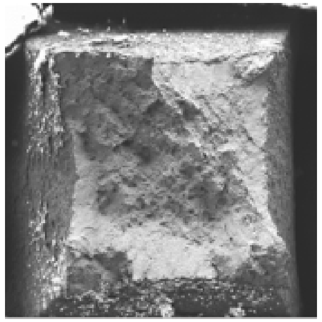


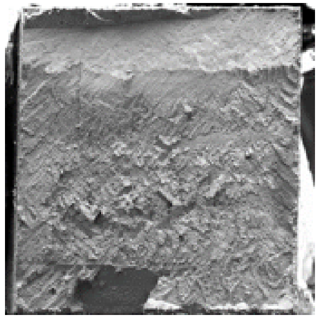


HT1: β

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

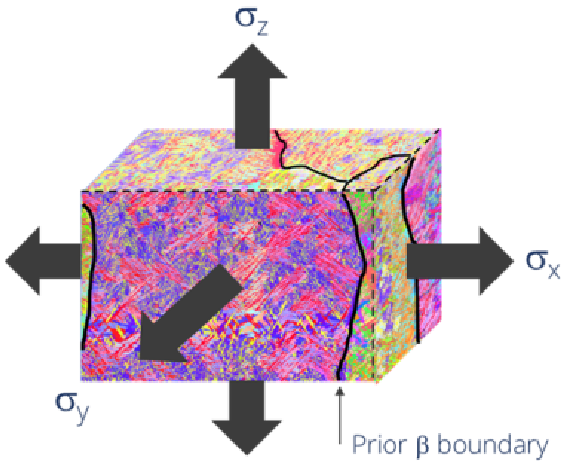


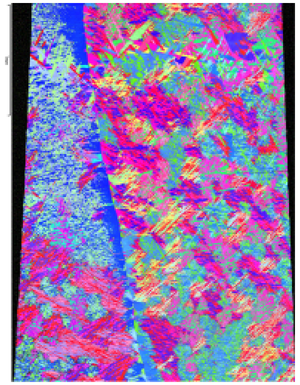


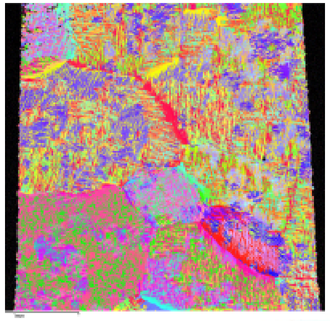


AB, HT2: α

Growth of continuous α at prior β results in lower strength compared to matrix

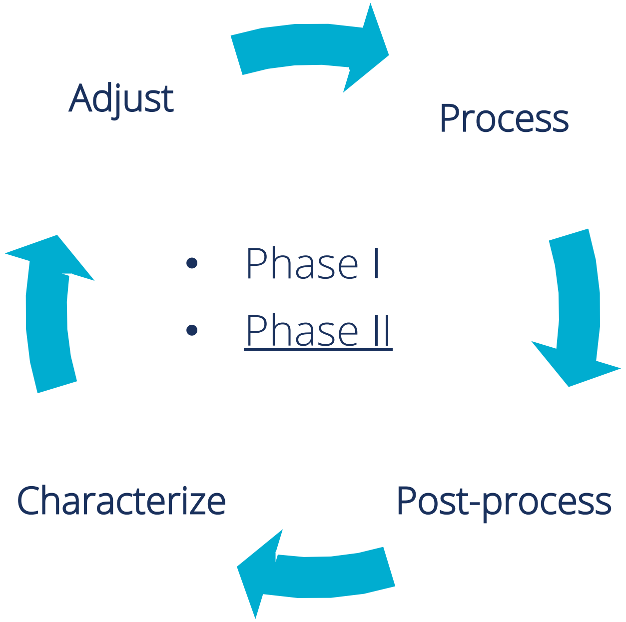


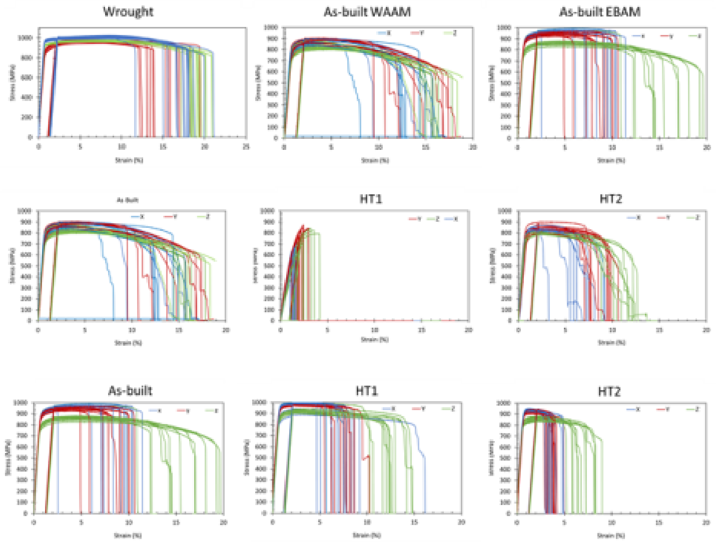




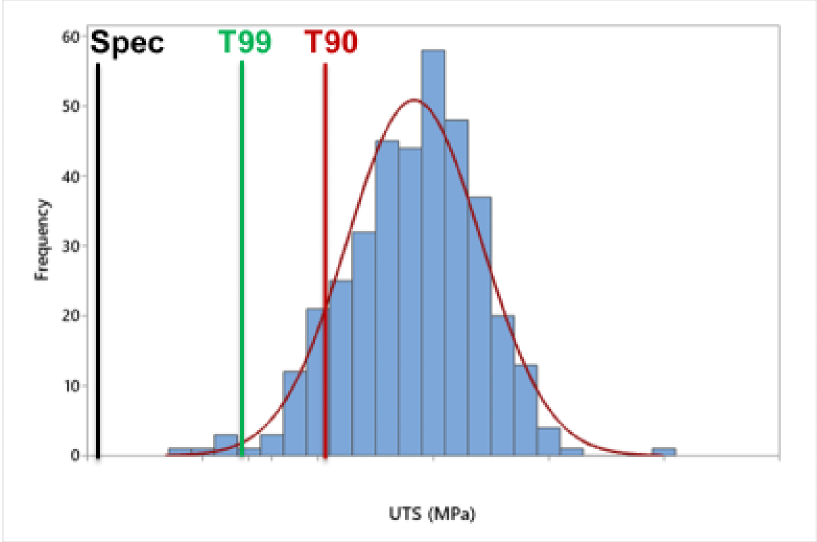
Conclusions/Outlook

- β anneal heat treatment did provide increasing strengths compared to the as built condition
- α anneal heat treatments do not provide convincing benefits to tensile properties
- Initial microstructure (cooling rate) plays a pivotal role in sub-transus heat treatments





Standard E8 Testing



Thank You!

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