SAND2022-9867C

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Exceptional service in the national interest

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

Natalia Saiz, Jonathan Pegues, Shaun Whetten, Andrew B. Kustas, Tyler Chilson

Solid FreeForm Fabrication Symposium

Austin, Texas

July 26, 2022

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Additive Manufacturing at SNL

Reduce Risk, Accelerate Development

- Simplify assembly & processing
- Prototypes, test hardware, tooling & fixturing

Sandia telescope

Printed battery

Add Value

- Design & optimize for performance
- Complex freeforms, internal structures, integration
- Engineered materials

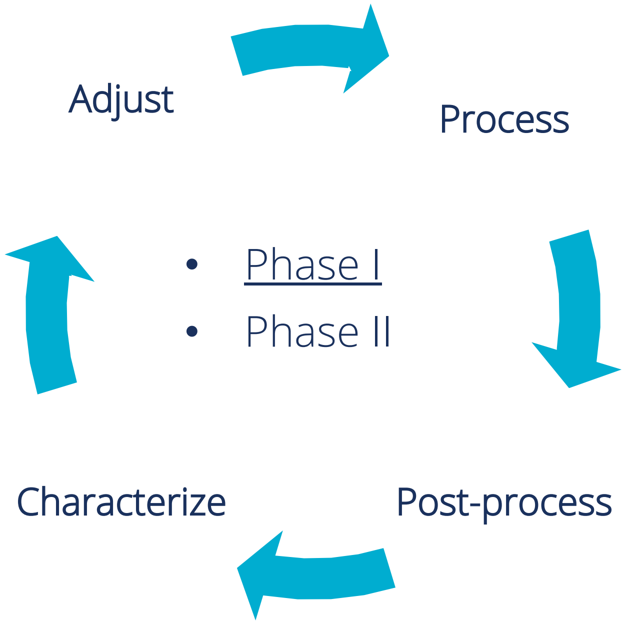
Full scale additive weapon mock-up

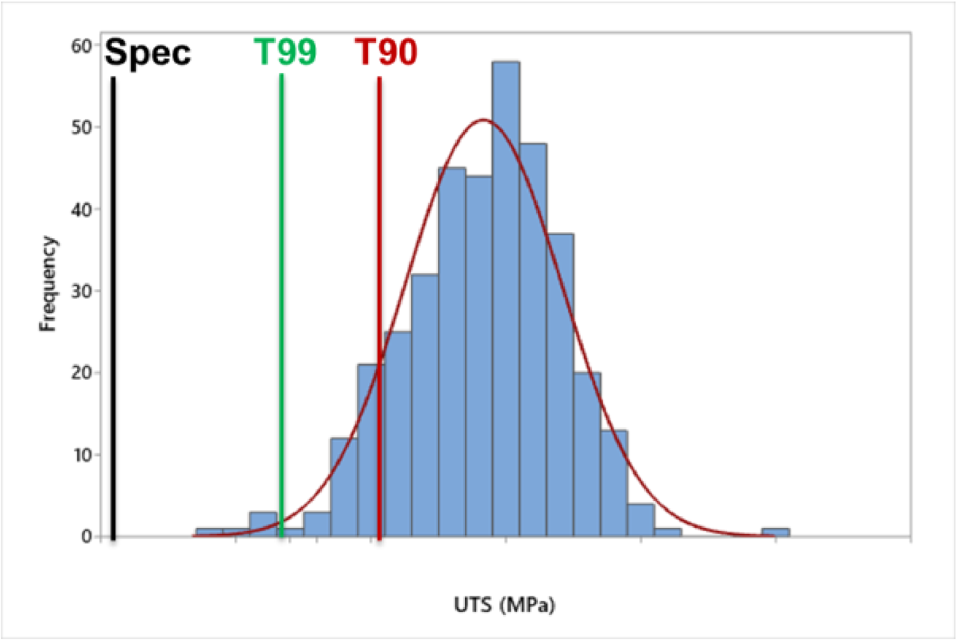
Continually Growing Interest Across Sandia Missions

Wire Directed Energy Deposition (W-DED): Background

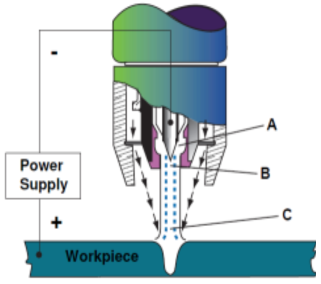
Objective: Provide <u>statistically validated</u> material specs and design margins for W-DED Ti-6Al-4V products

- 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

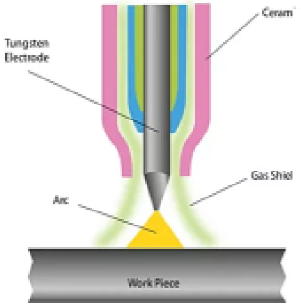




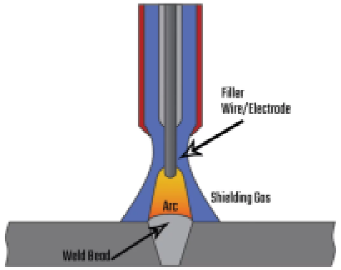
Additive Manufacturing: W-DED



Plasma Arc



Tungsten Arc

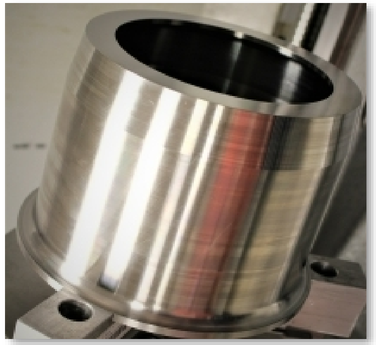


Metal Arc

WAAM: Hybrid

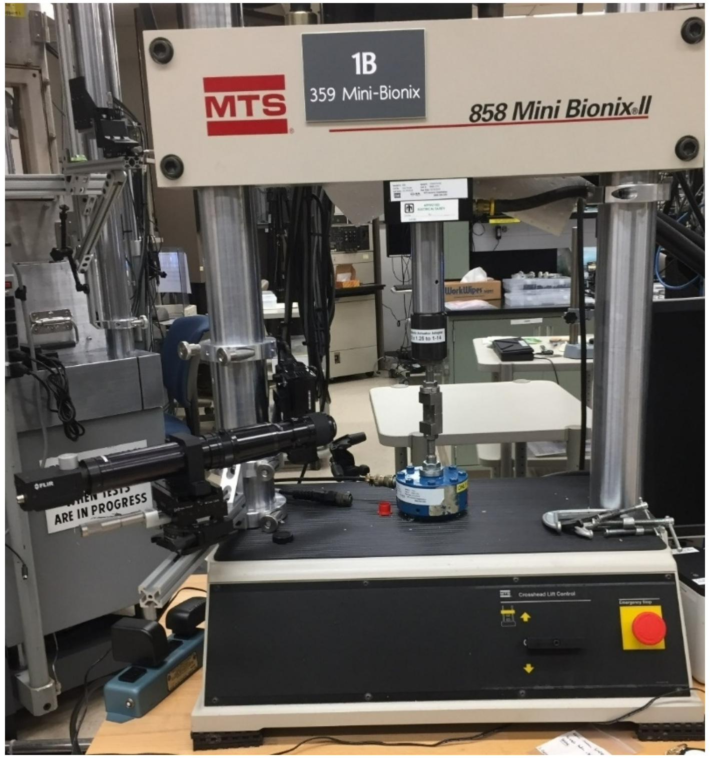
Pre-form

Machined

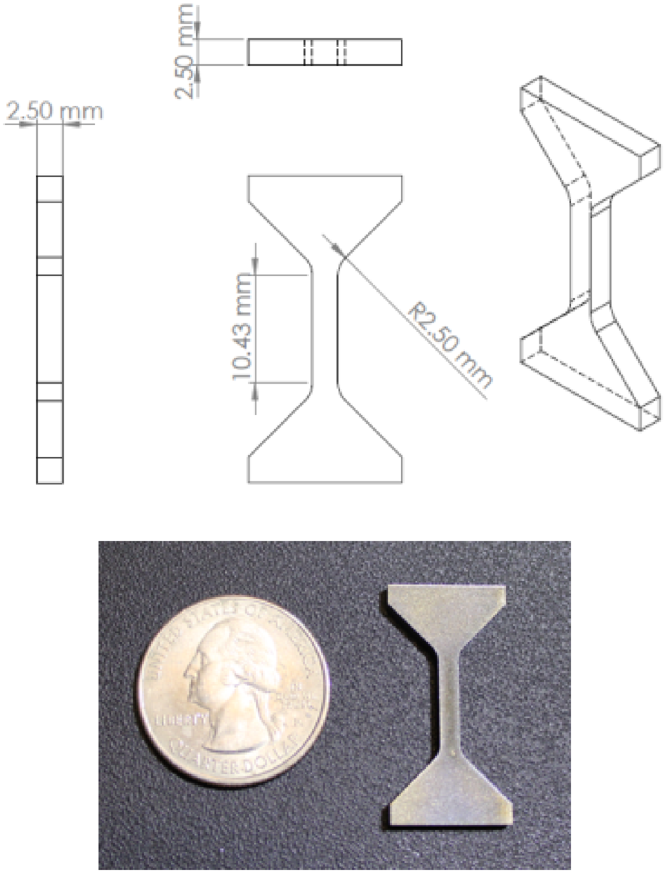


High Throughput Testing

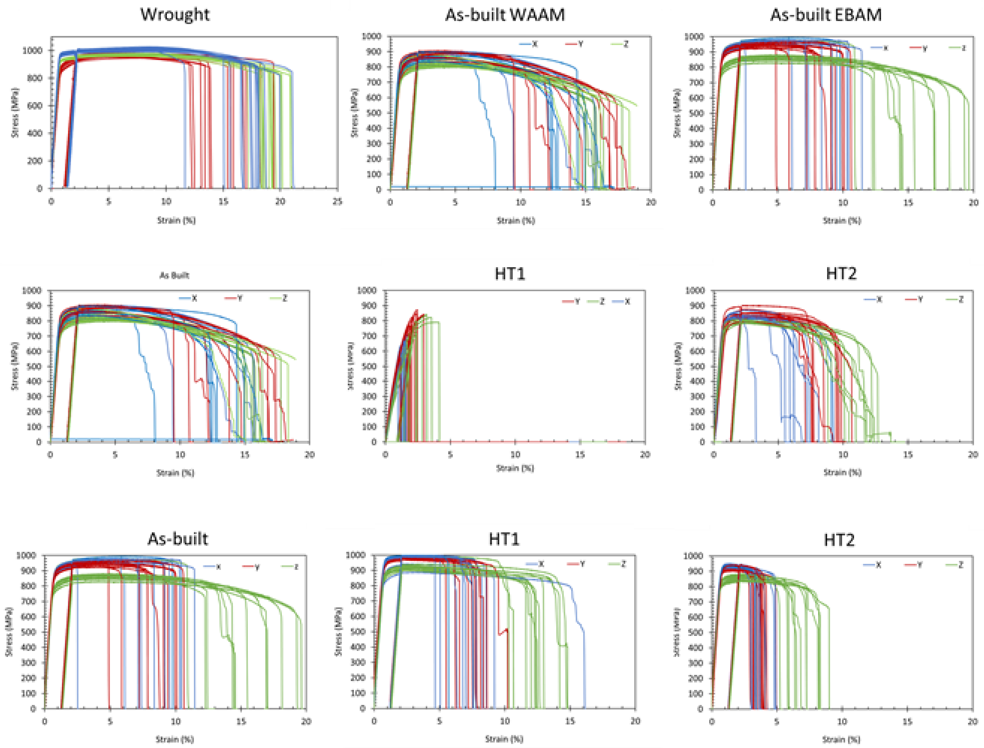
MTS: 858 5-kip frame



Specimen Geometry

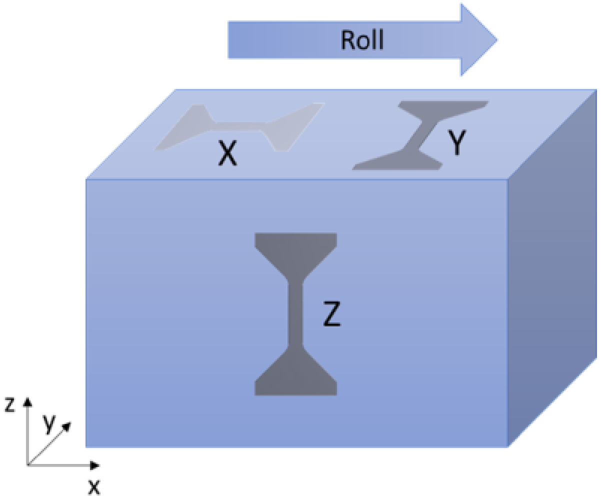


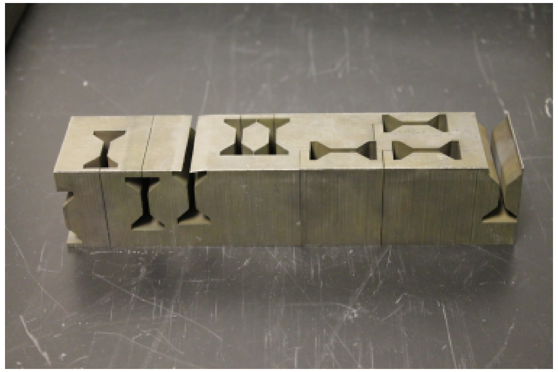
Rapid development of statistically relevant tensile data



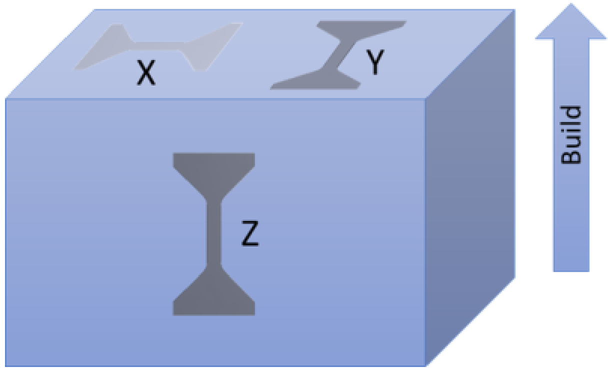
Orientation of Wrought and Additive Manufactured Tensile Samples

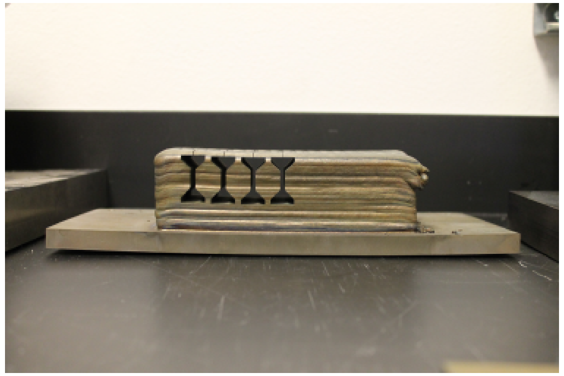
Mill Annealed

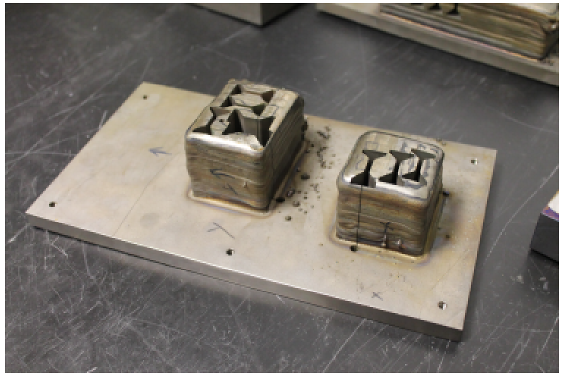




W-DED







Conventional Process

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

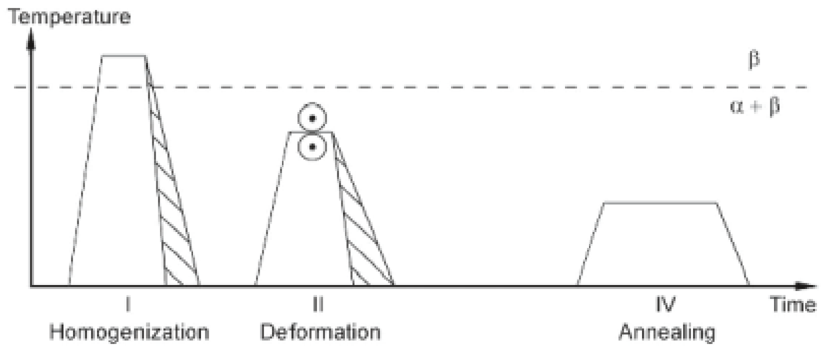
AM Process

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

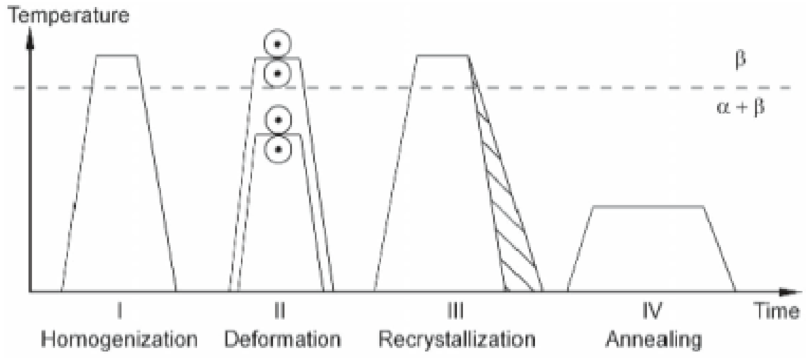
Conventional vs. Additive Manufactured

Wrought:

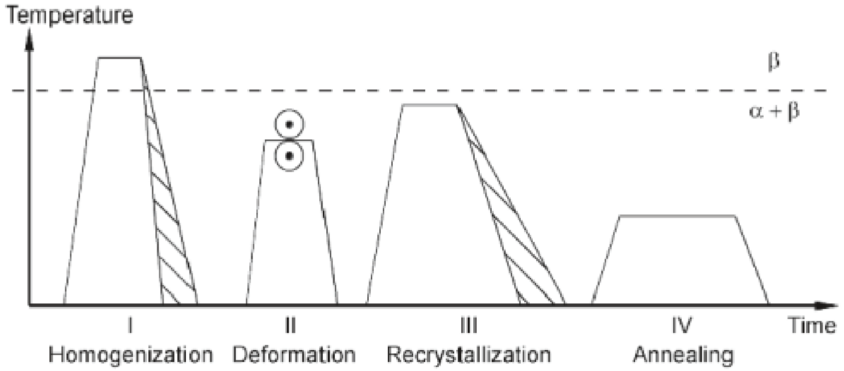
Mill Anneal



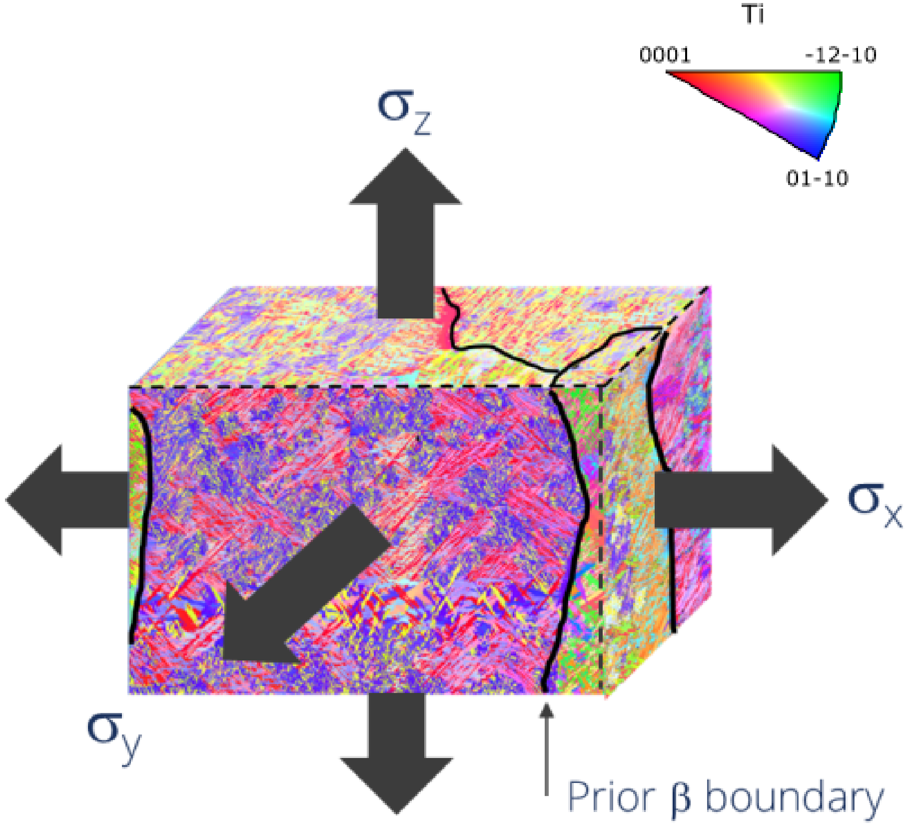
β Anneal



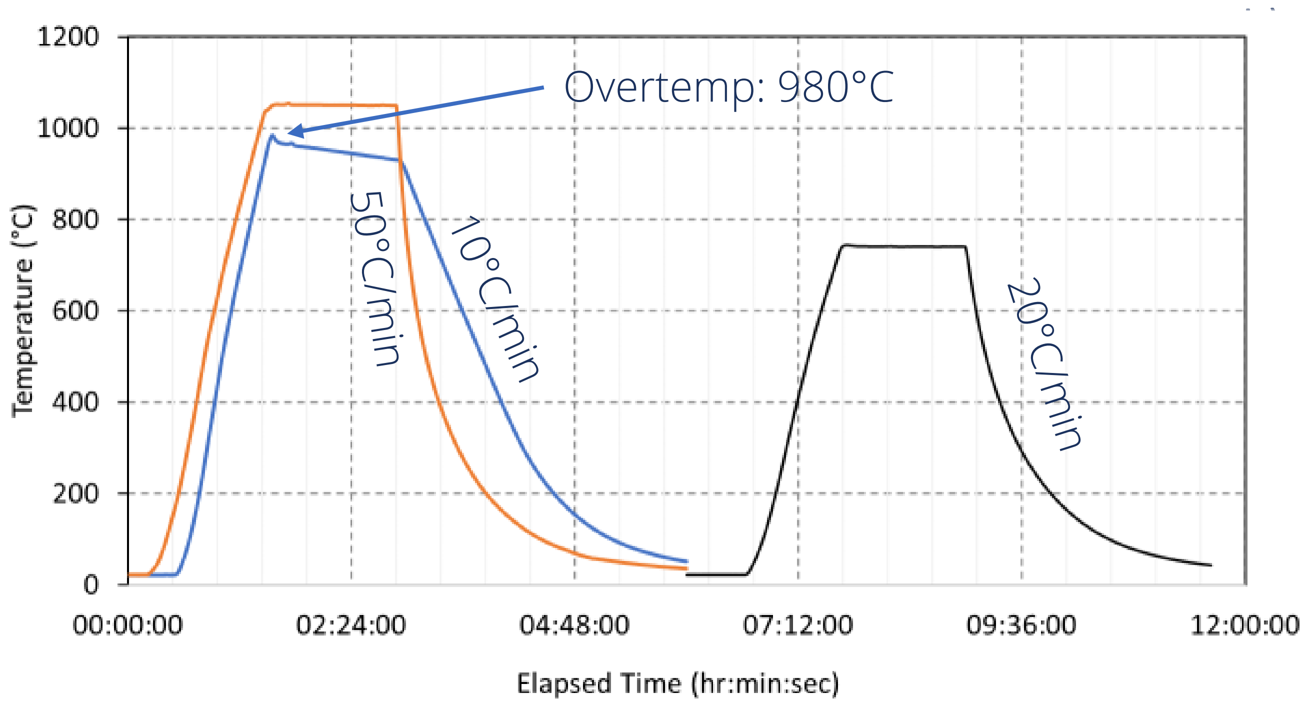
α+β Anneal



Anisotropy



Heat Treatments



Heat Treatment 1:

Beta anneal at 1050°C for 1 hour

Overage Anneal at 725°C in a 2 hour soak

Argon Quench

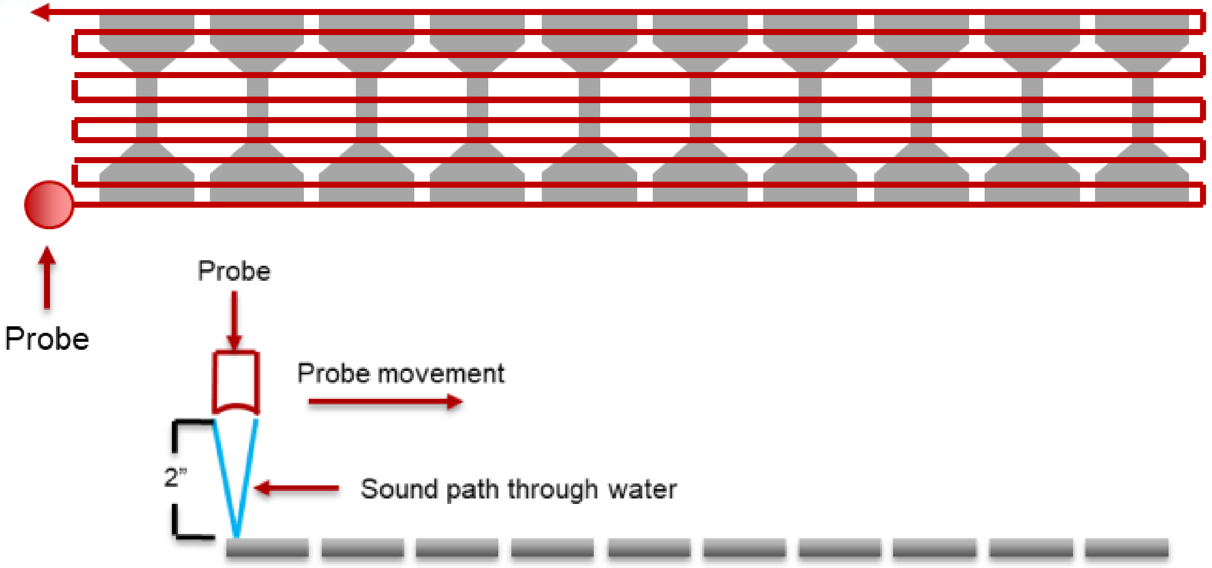
Heat Treatment 2:

Alpha/Beta anneal at 926°C for 1 hour

Overage Anneal at 725°C in a 2 hour soak

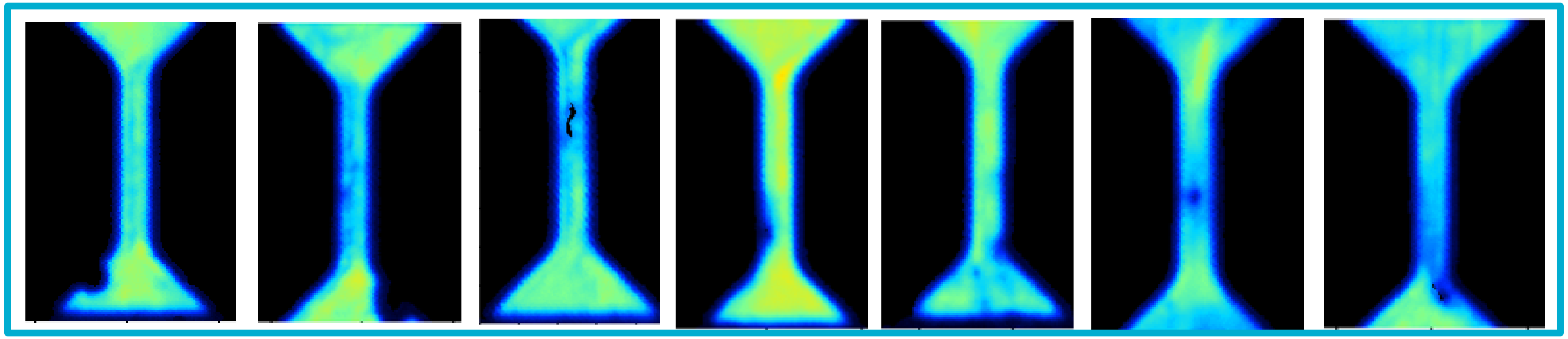
Argon Quench

Immersion Ultrasonic Inspection

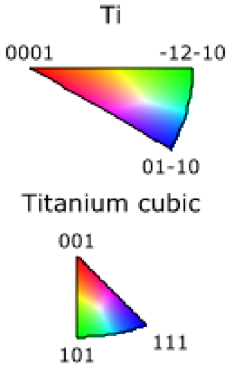


- Immersion inspections were performed from the etched surface
- ~50 μm resolution and at a height of 50 mm above side being scanned
- No observable defects discovered for wrought material
- Low porosity observed for WAAM

WAAM



Wrought & As-built WAAM Microstructures

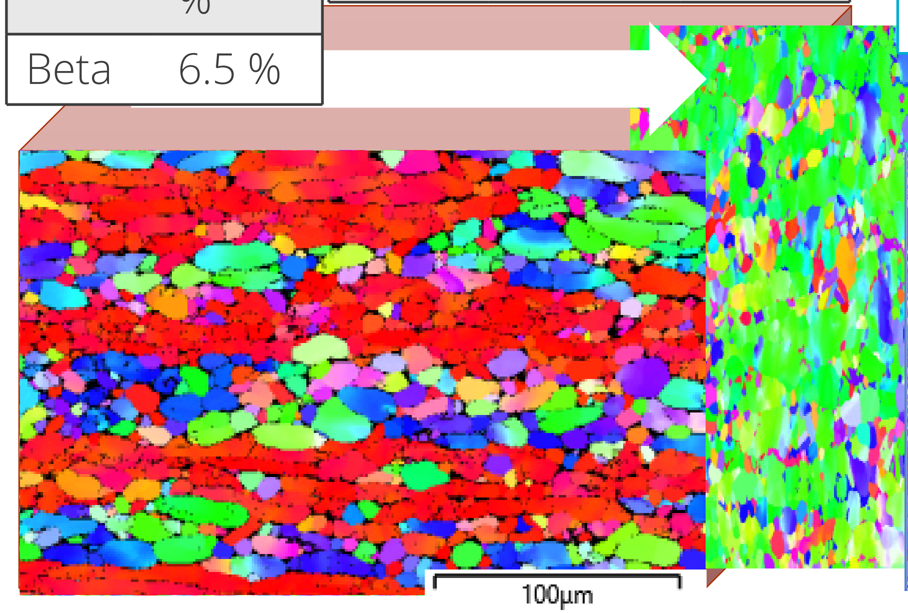


Wrought

Phas e	At. %
Al	6.84
V	3.77
Fe	0.14

Phas e	Fract.
Alpha	93.4 %
Beta	6.5 %

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

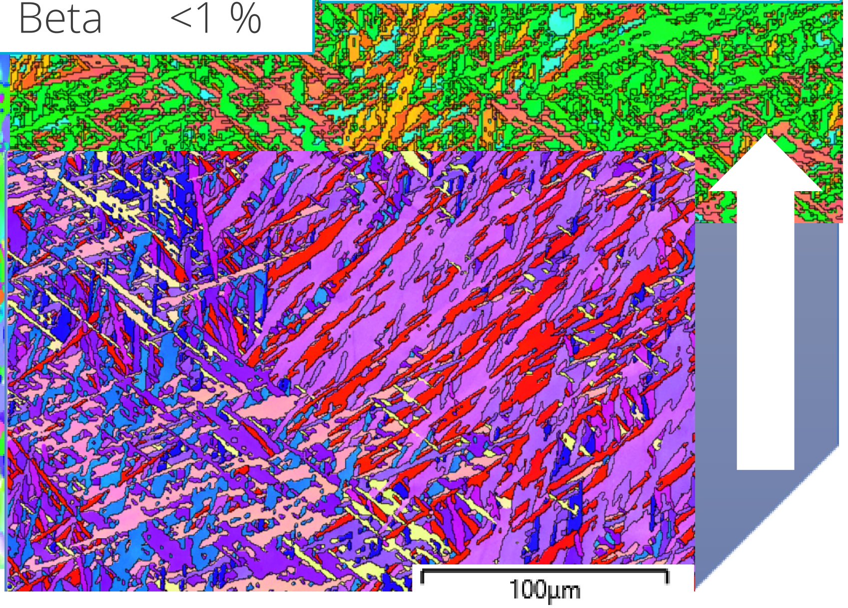


WAAM

Phas e	At. %
Al	6.05
V	3.68
Fe	0.12

Phas e	Fract.
Alpha	99 %
Beta	<1 %

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



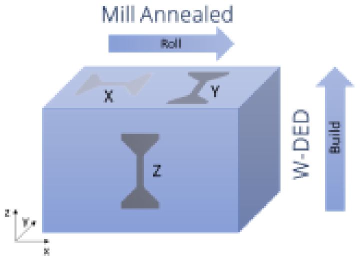
Ti-6Al-4V Compositions

Phase	At.%
Al	5.5 - 6%
V	3.5 - 4.5%
Fe	< 0.40%

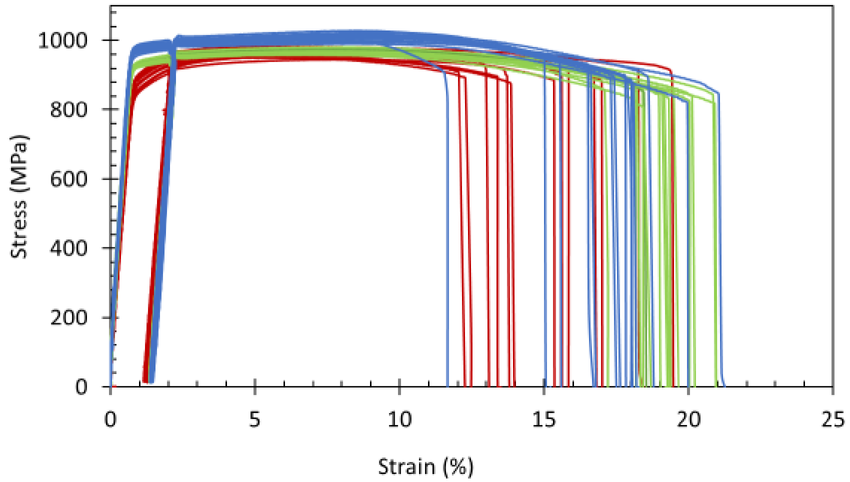
Wire Feed Stock Composition

Phase	At.%
Al	6.75%
V	4.50%
Fe	0.15%

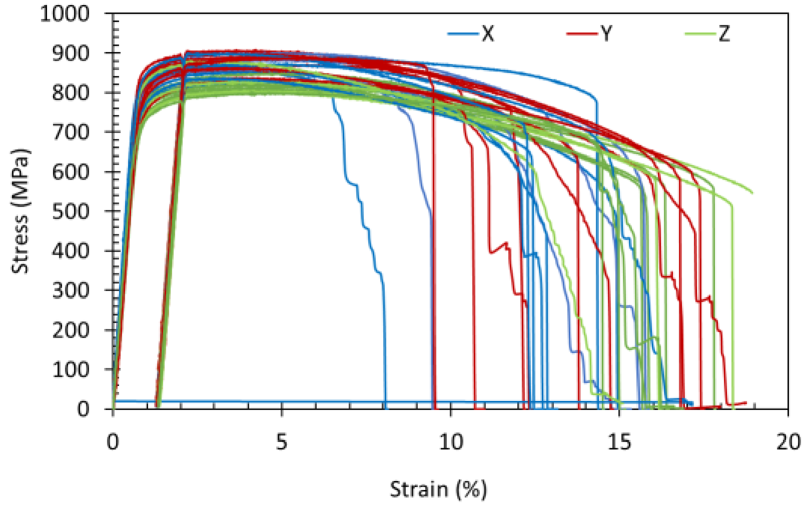
Wrought & As-built WAAM Tensile Properties

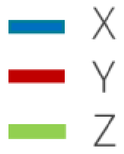


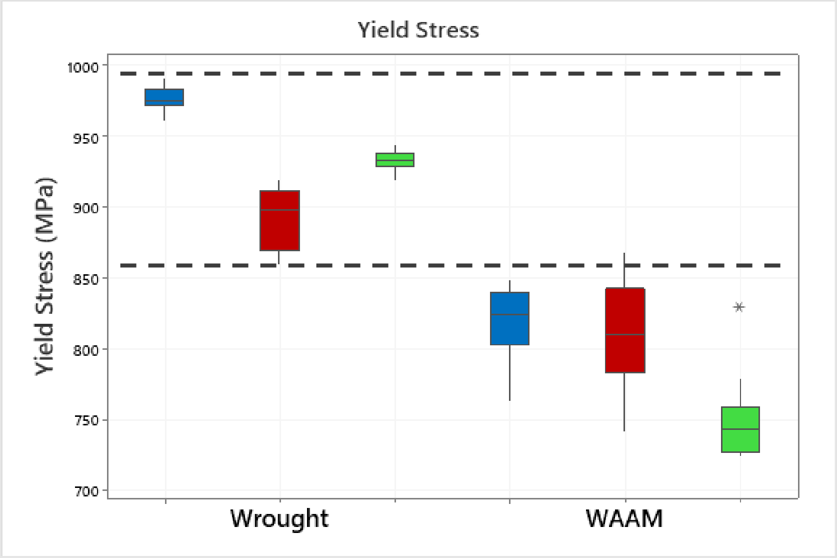
Wrought

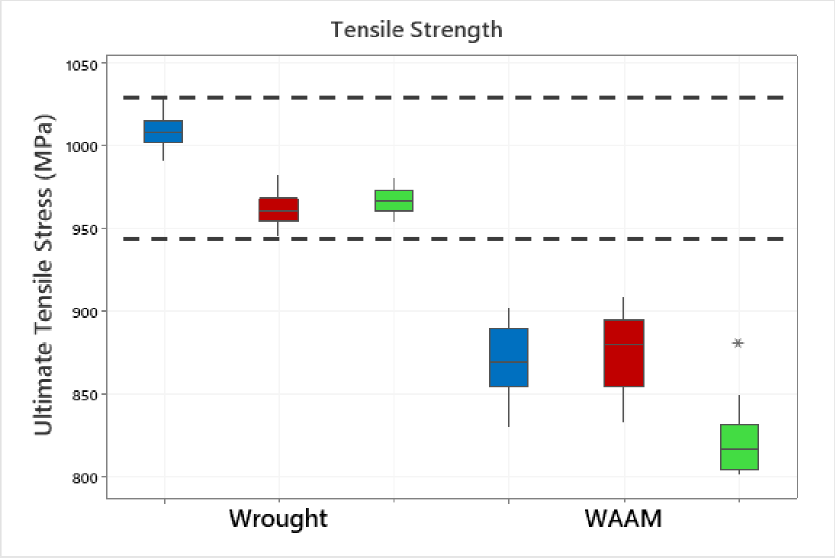


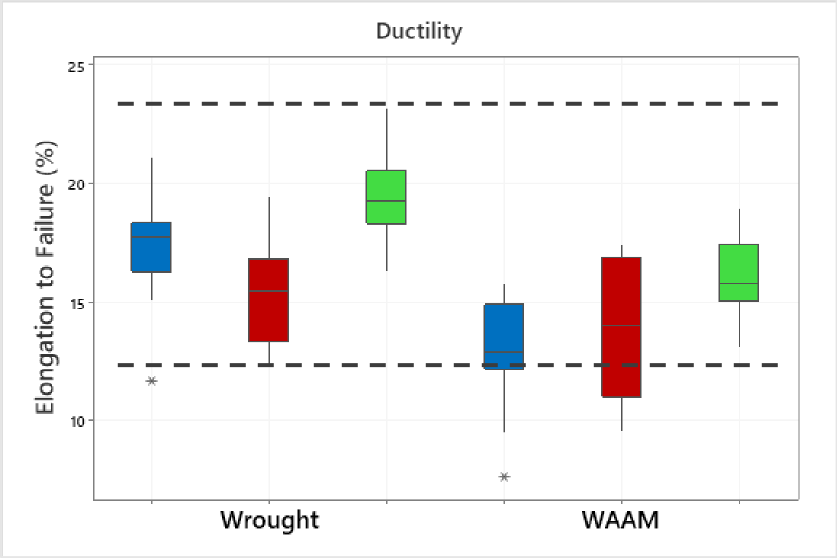
As-built WAAM



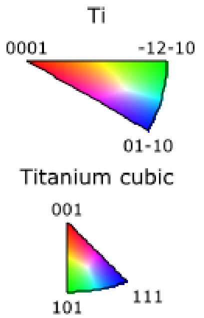








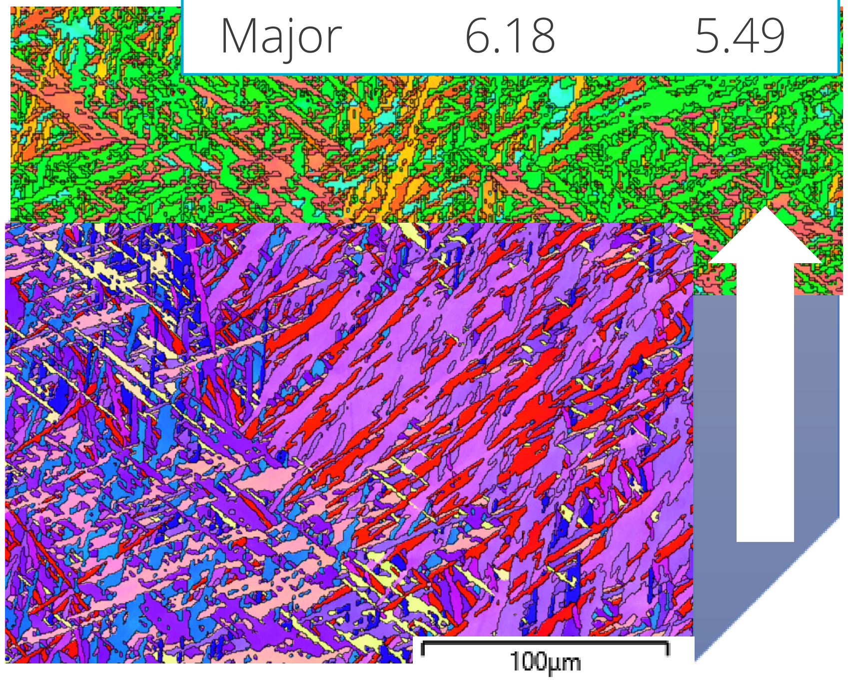
WAAM: Microstructures



WAAM

Phase	Fraction
Alpha	99%
Beta	< 1%

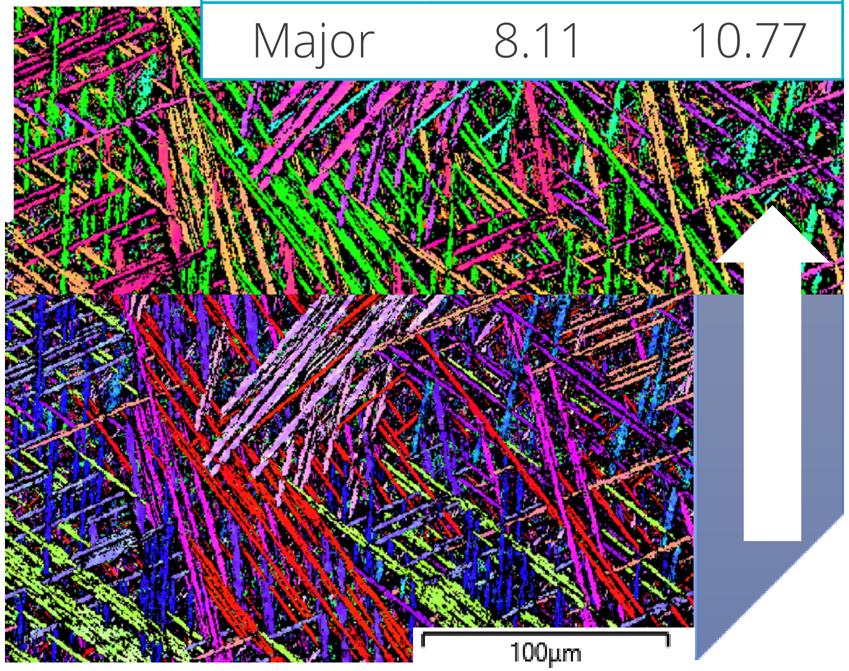
	Average (µm)	Std (µm)
Minor	1.67	0.89
Major	6.18	5.49



HT1: β

Phase	Fraction
Alpha	99%
Beta	< 1%

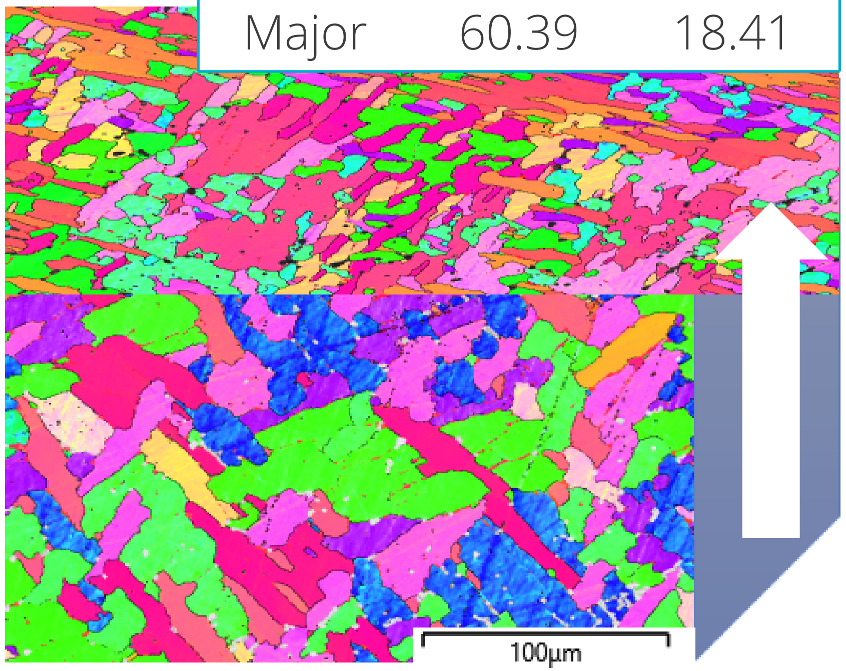
	Average (µm)	Std (µm)
Minor	2.34	1.46
Major	8.11	10.77



HT2: α+β

Phase	Fraction
Alpha	95.9%
Beta	2.0%

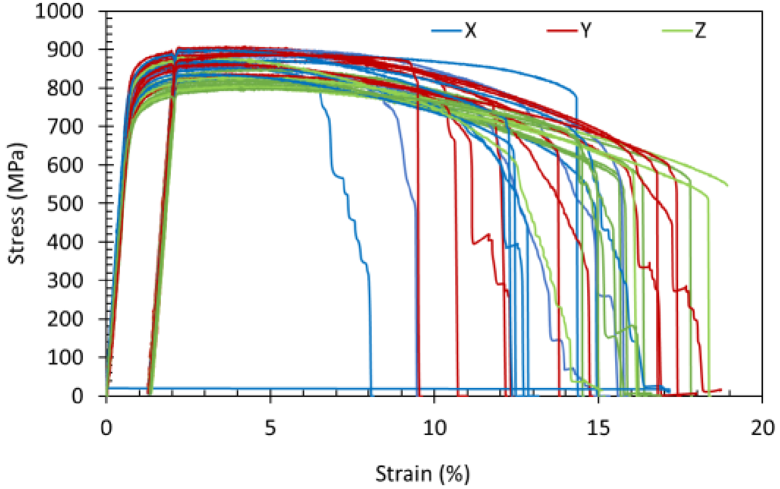
	Average (µm)	Std (µm)
Minor	27.98	9.1
Major	60.39	18.41



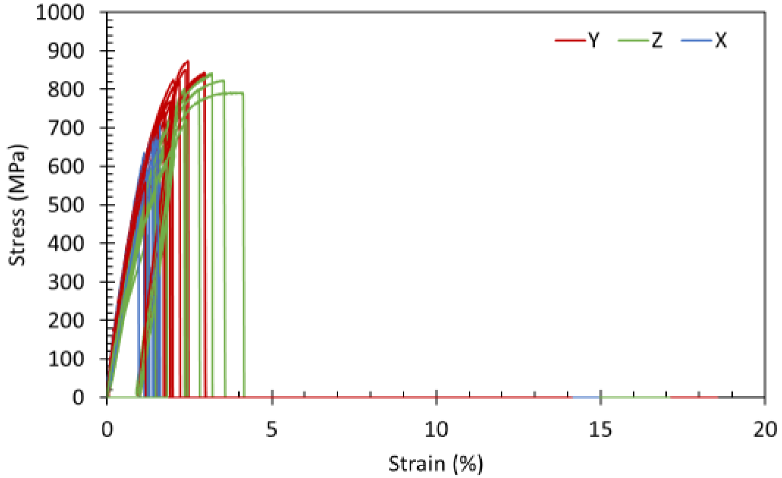
HT1 & HT2 WAAM Tensile Property Results

X
Y
Z

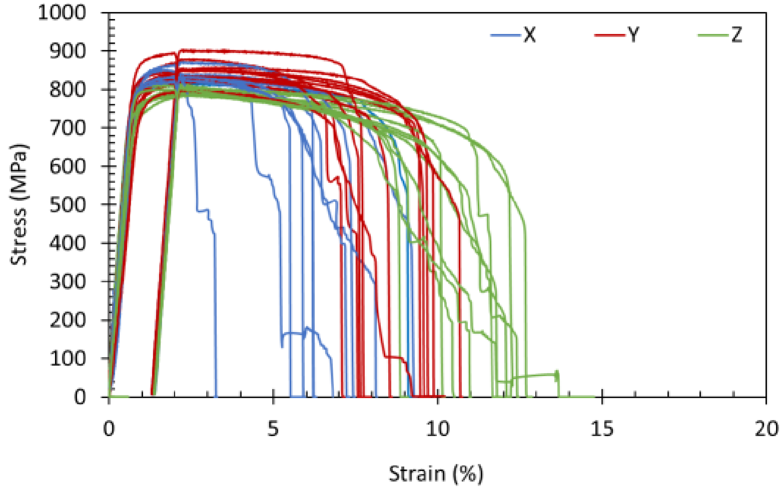
As Built

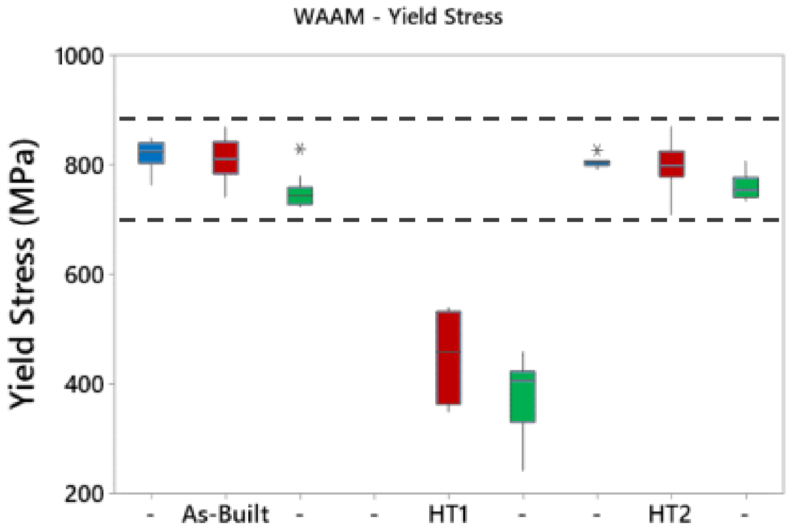


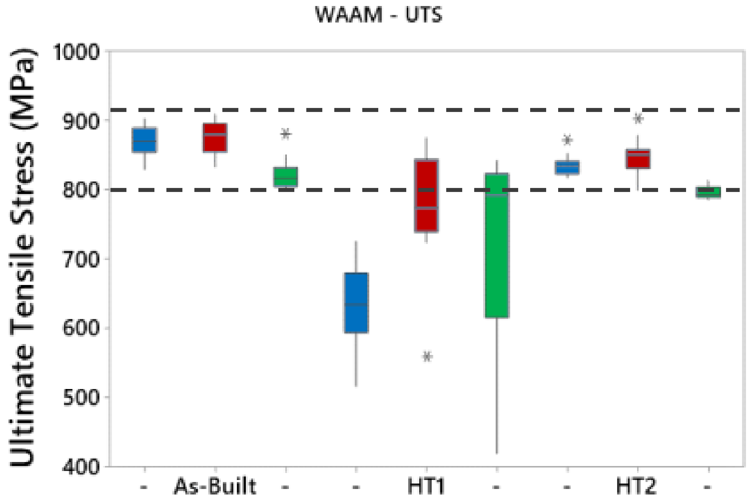
Beta

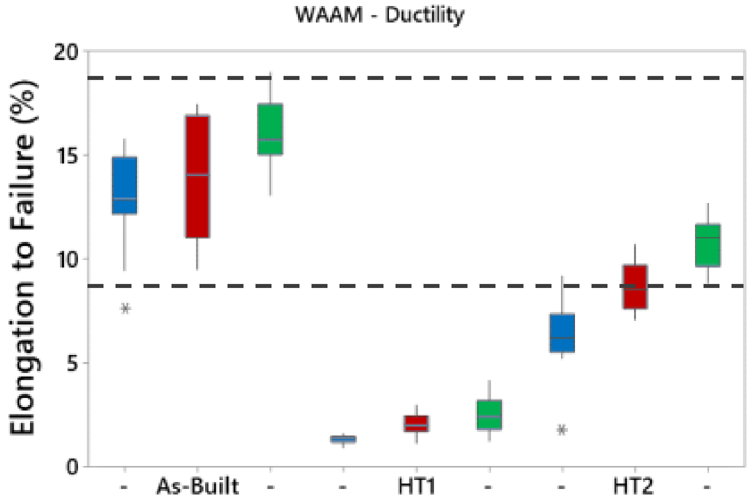


Alpha + Beta

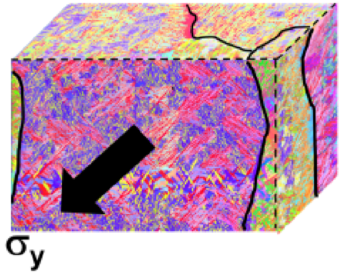








Fractography: WAAM



WAAM-AB

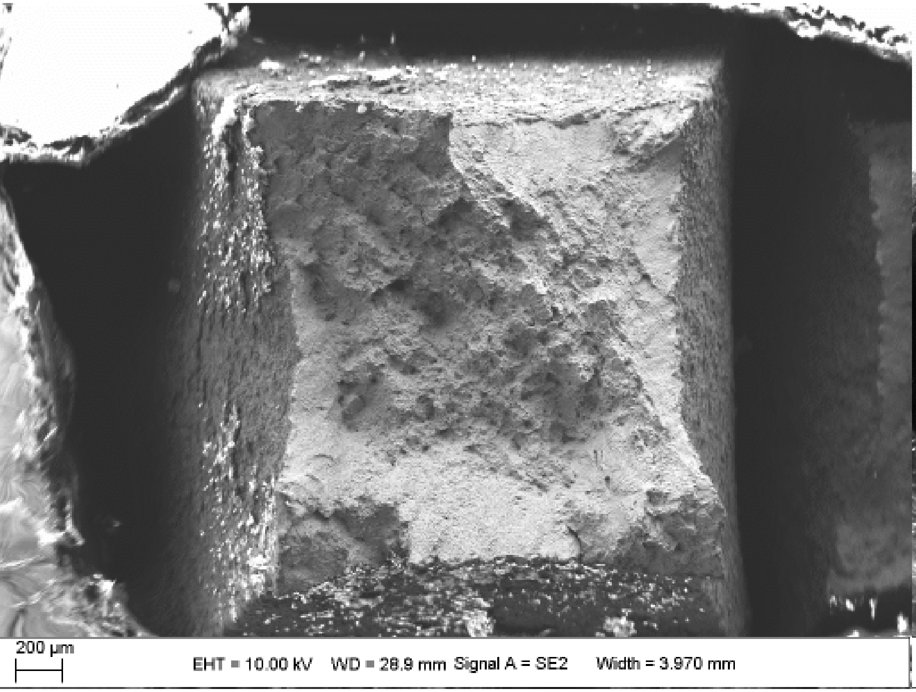
Ductile Transcrystalline fracture

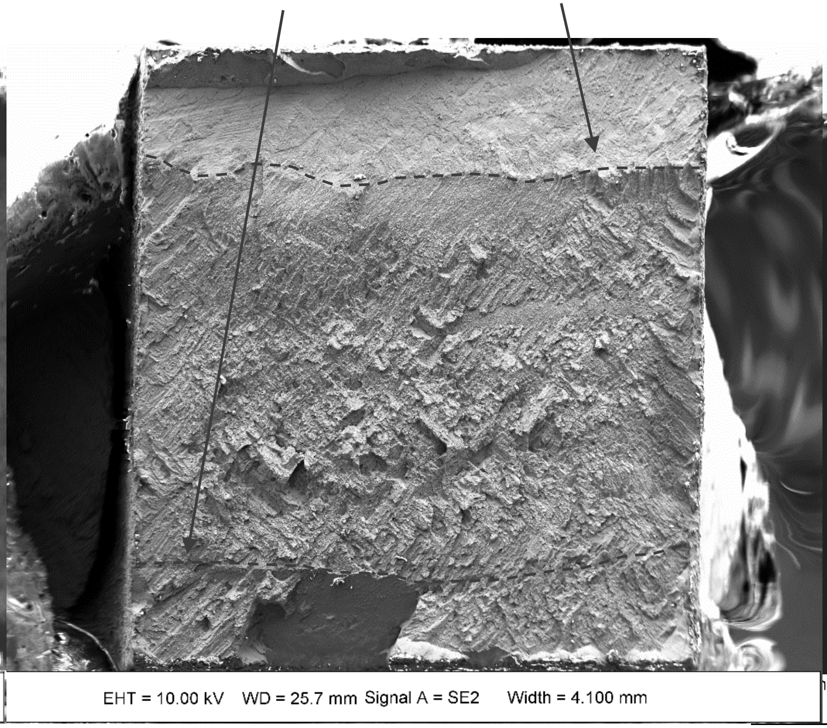
HT1: β

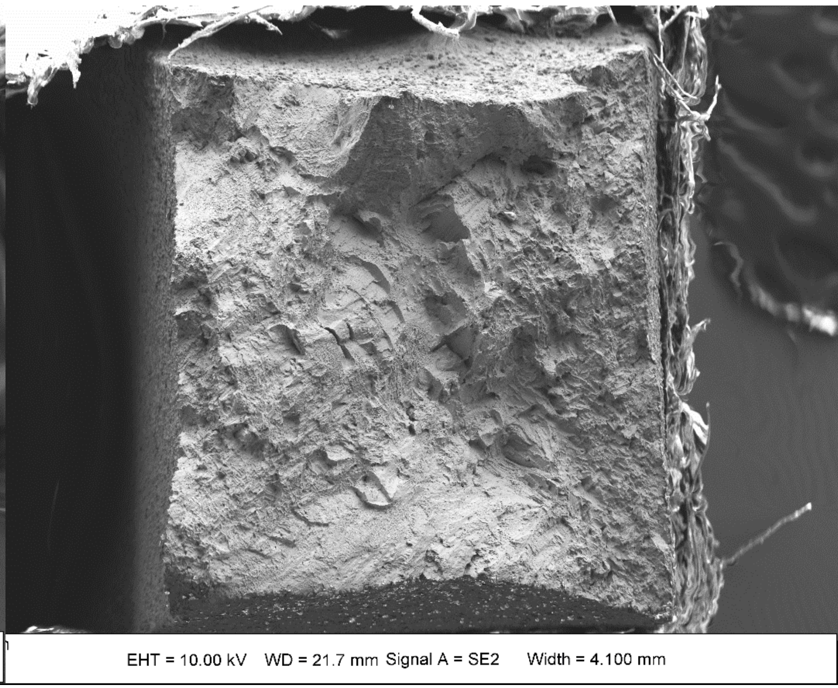
Intercrystalline fracture along continuous α

HT2: α+β

Mix of Ductile/Brittle Transcrystalline & Intercrystalline fracture



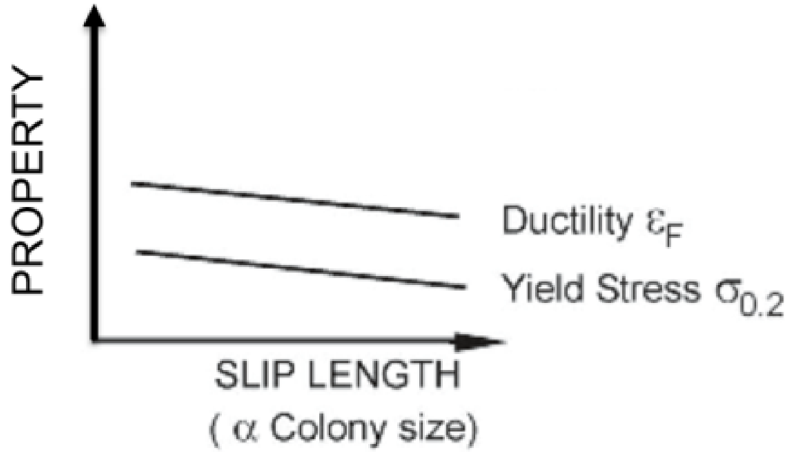




Competing Failure Mechanisms

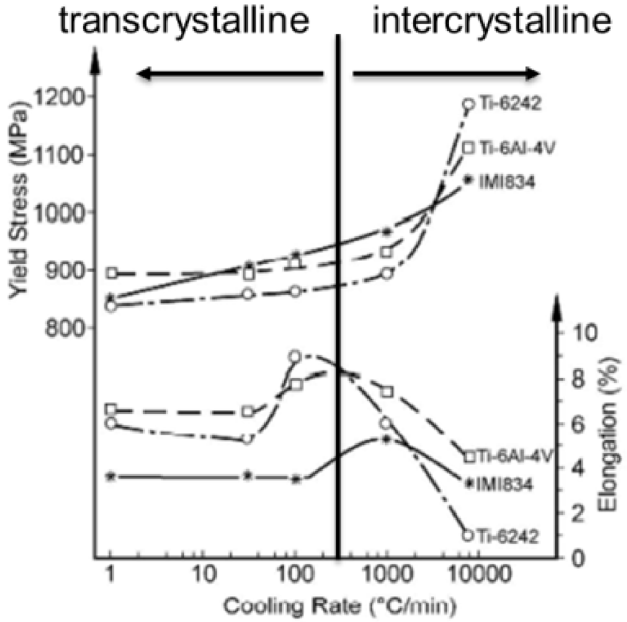
AB, HT1: β

Cooling rates affect the slip length/colony size



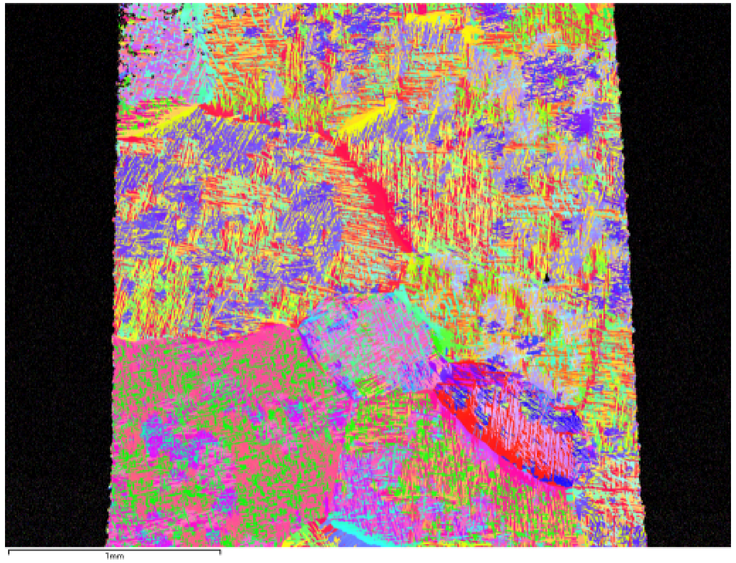
HT1: β

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



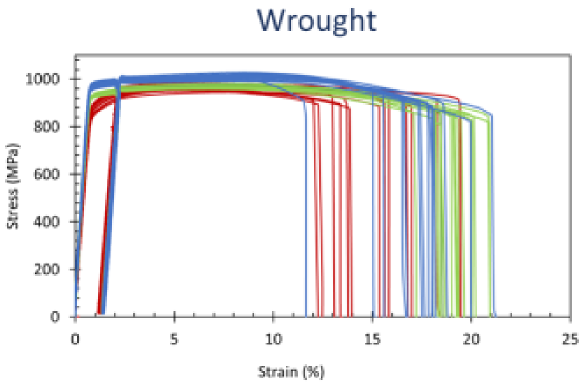
AB, HT2: α+β

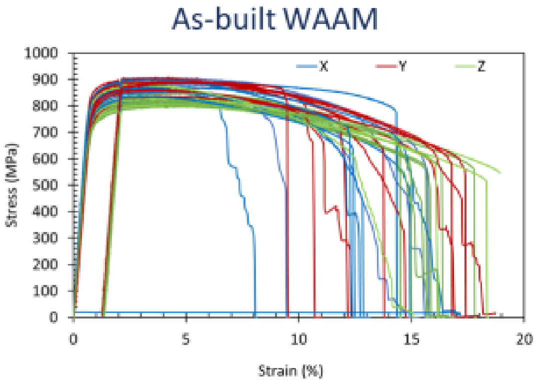
Growth of continuous α at prior β results in lower strength compared to matrix

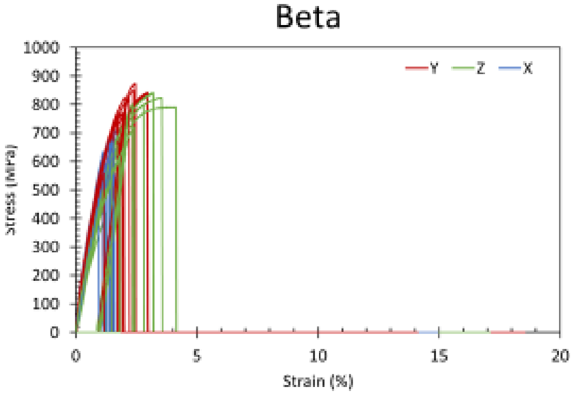


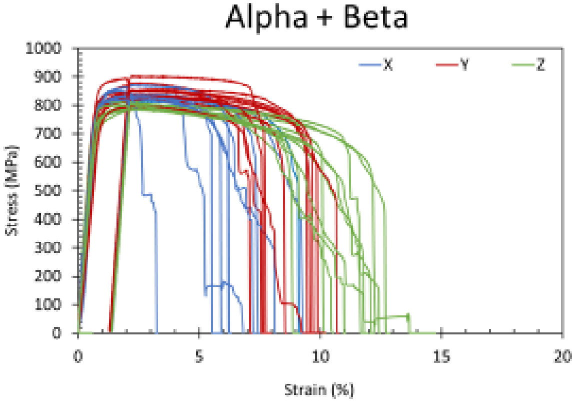
Conclusions/Summary

- β & (α + β) field heat treatments do not provide convincing benefits to WAAM tensile properties
- Microstructure plays a greater role in failure than defects for both W-DED processes
- Initial microstructure plays a pivotal role in final grain size after heat treatment









Continuing the Experiment

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

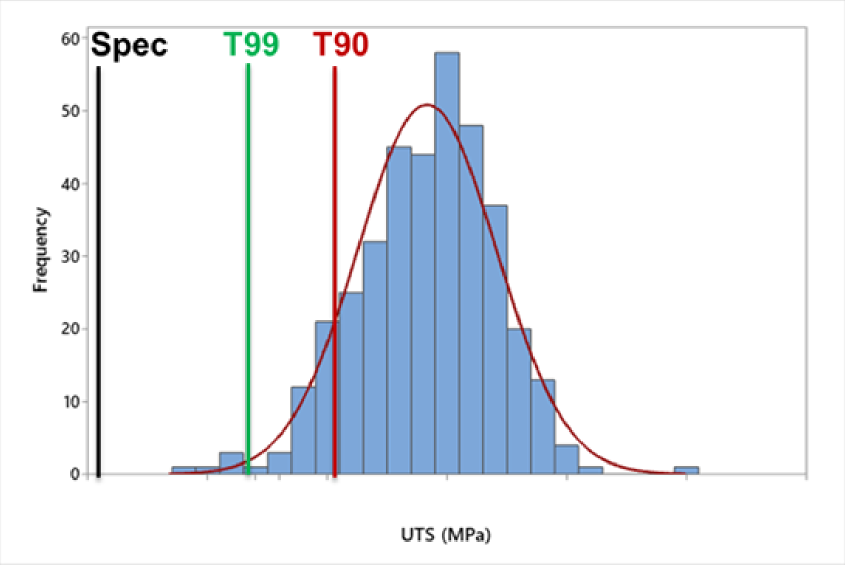
Adjust process

Process

- Phase I
- Phase II

Post-process

Characterize



Thank You!

Natalia Saiz, Sandia National Laboratories (SNL)

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

July 27, 2022 at 3:20 pm

Presenter: Jonathan Pegues, Sandia National Laboratories (SNL)

Hot Isostatic Pressing to Increase Isotropic Behavior of Wire DED Ti-6Al-4V

July 27, 2022 at 2:15 pm

Presenter: LaRico "Rico" Treadwell, Sandia National Laboratories (SNL)

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

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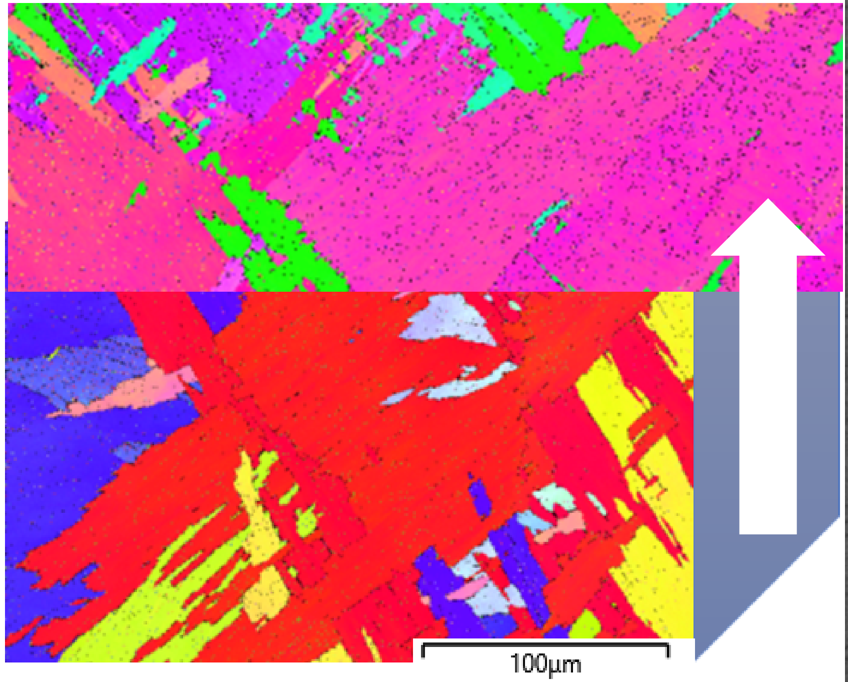
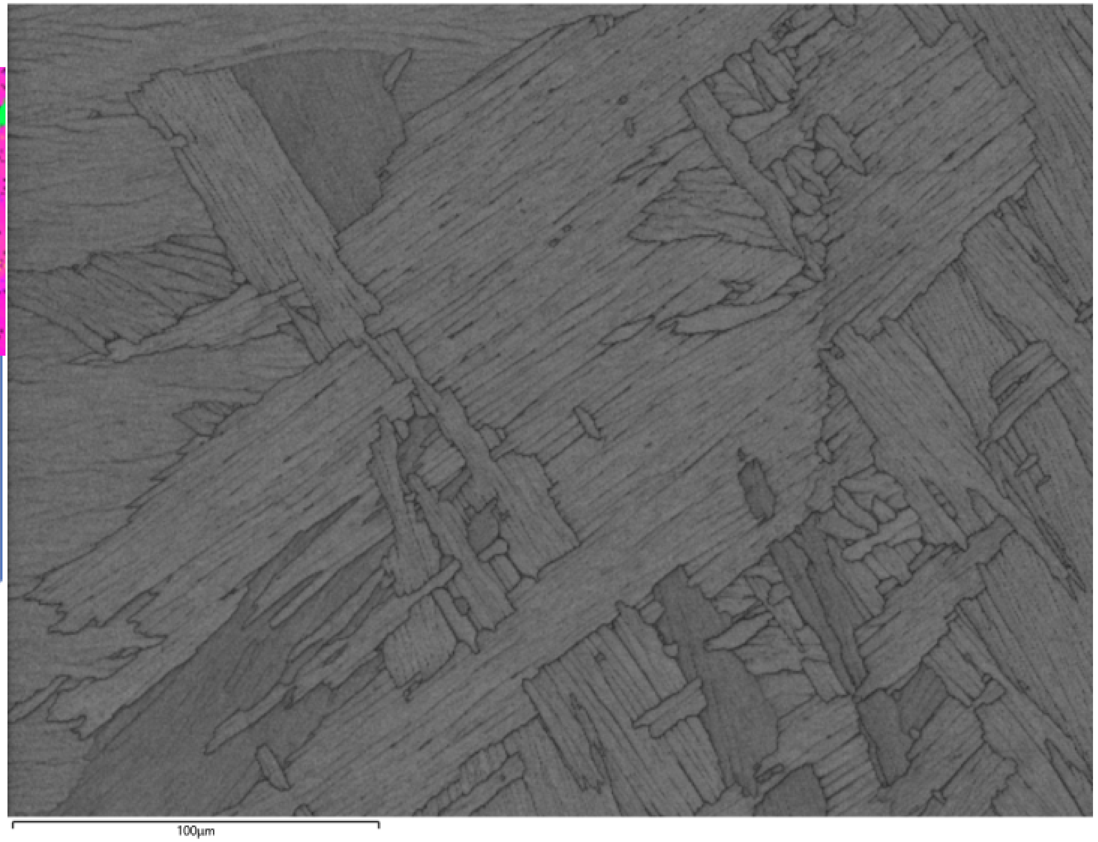
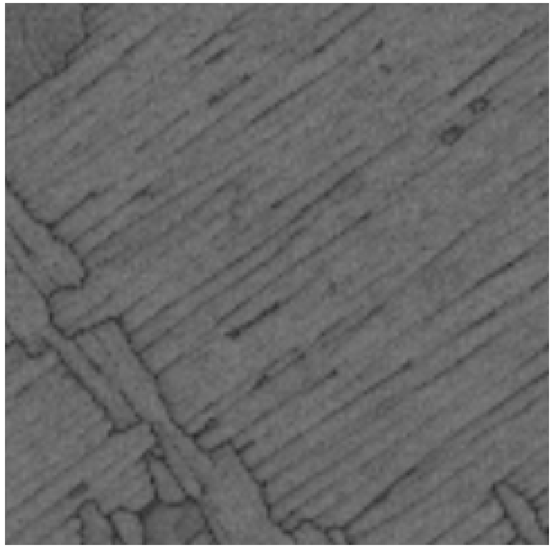
Colony vs Lamellar







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