UCFER review meeting

UCFER RFP 2020-06 / DE-FE0026825

Wire Arc Additive Manufacturing of Advanced Steam Cycle Components Using Location Specific Design Enhanced by High-Throughput Experiments and Machine Learning

PMMD

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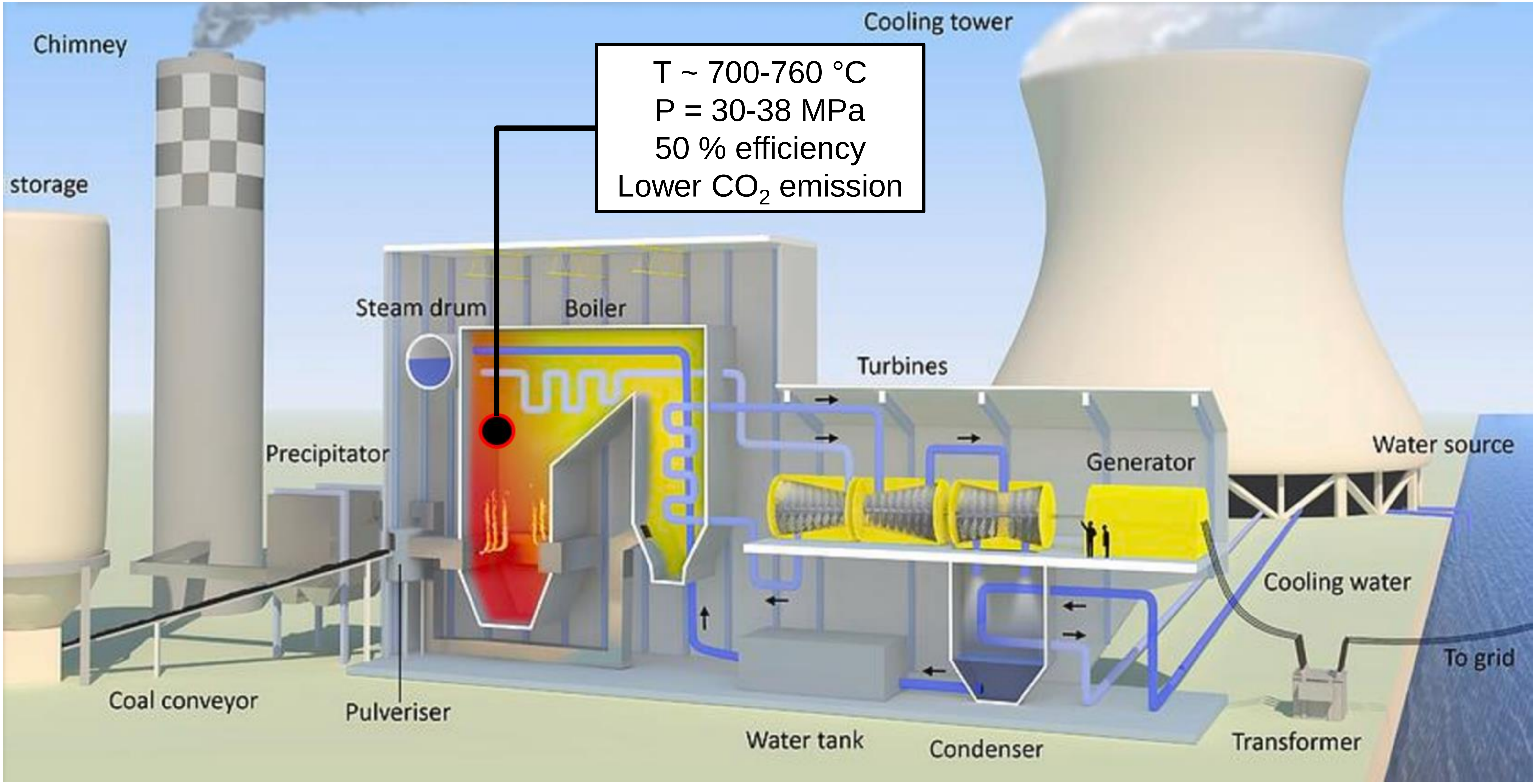
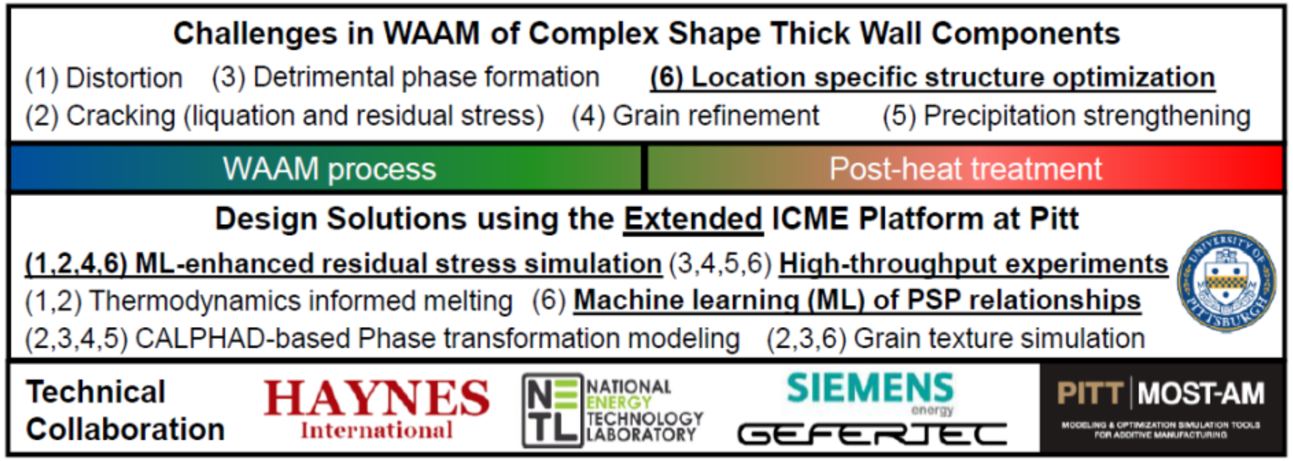
Outline

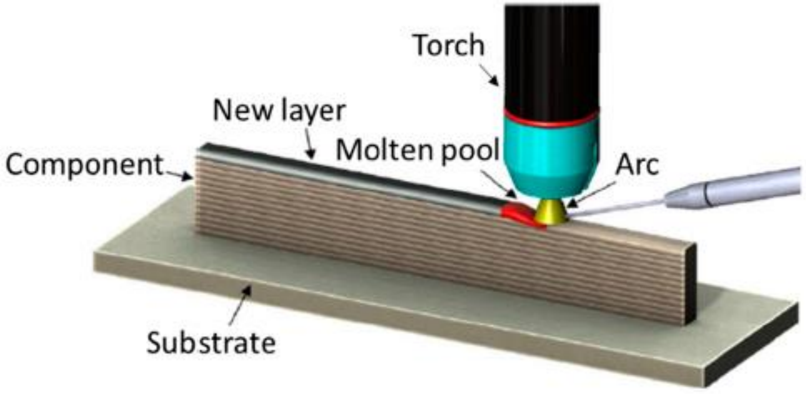
- Background
- Recrystallization studies
- Grain structure modeling
- γ' precipitation behavior
- Builds for high-throughput experiments
- Future work

Motivation: A-USC Coal Power Plants Eco-Efficiency



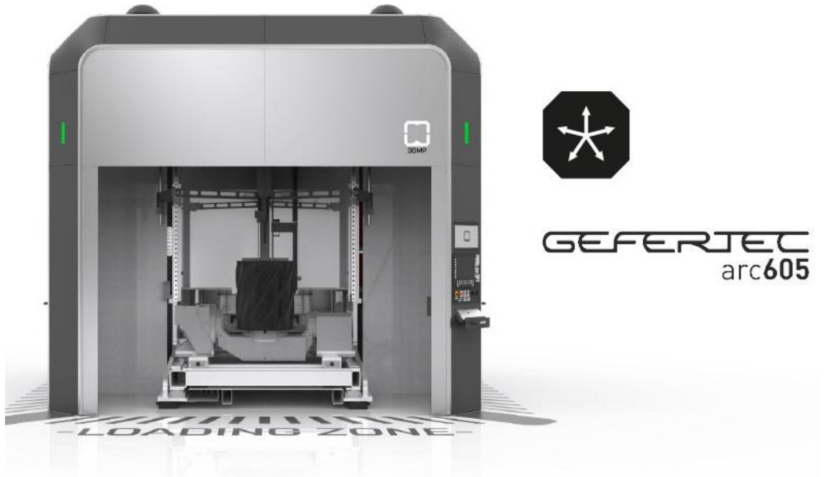
Wire Arc Additive Manufacturing (WAAM)





T.A. Rodrigues, Materials. 12 (2019).

- AM process that is similar to directed energy deposition
- Uses electric arc as heat source
- Solid wire is the feedstock material
- Main advantages are
  - high deposition rates
  - minimum wastage of materials
- Low running cost and short production cycle
- Ability to build large parts
- Main disadvantage is
  - lower precision in as-built parts

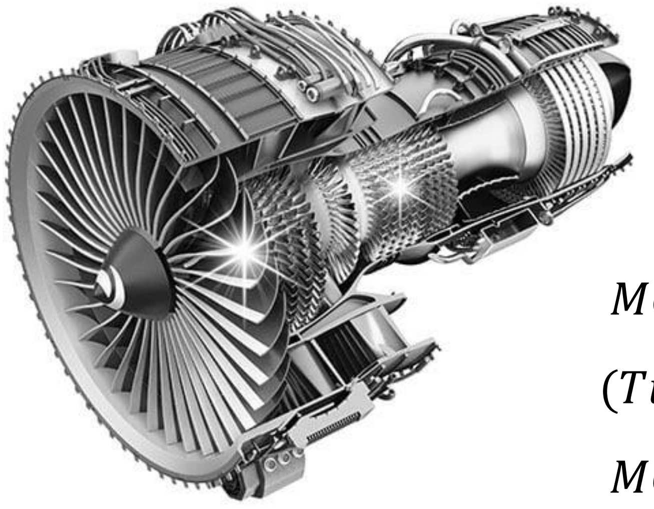


ARC 605 : 5-axis machining: Production of metallic components up to 0.8 m³ with a maximum mass of 500 kg.

Haynes 282

Chemical Resistance
- Oxidation
- Corrosion

Mechanical Resistance
- Traction
- Fracture
- Impact
- Creep



Primary TiN and Ti, Mo-rich MC phases

Secondary/Primary Mo-Ni rich M_6C and Cr, Mo-rich $M_{23}C_6$ carbides

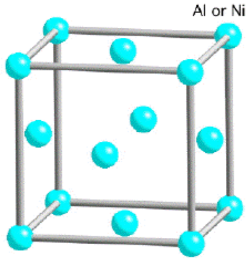
$$MC + \gamma \rightarrow M_{23}C_6 + \gamma'$$

$$(Ti, Mo)C + (Ni, Cr, Al, Ti) \rightarrow Cr_{21}Mo_2C_6 + Ni_3(Al, Ti)$$

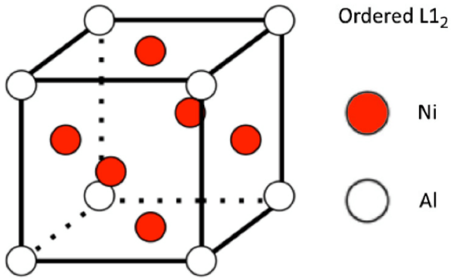
$$MC + \gamma \rightarrow M_6C + \gamma'$$

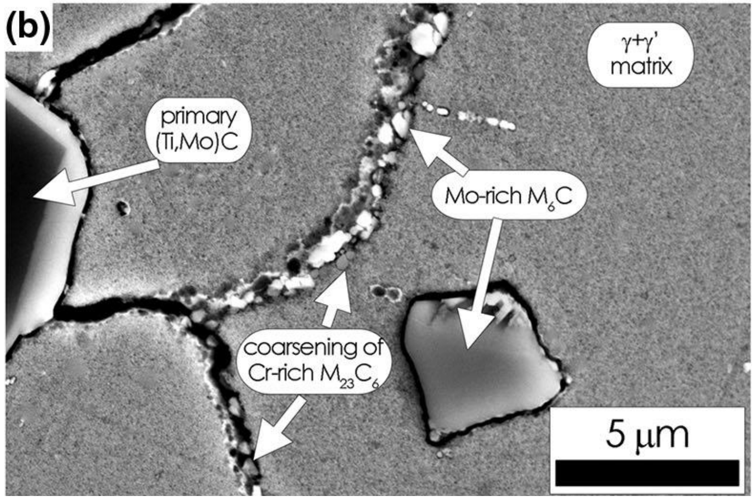
$$(Ti, Mo)C + (Ni, Cr, Al, Ti) \rightarrow Mo_3(Ni, Co)_3C_3 + Ni_3(Al, Ti)$$

γ phase , fcc



γ' phase (L12),$Ni_3(Al, Ti)$

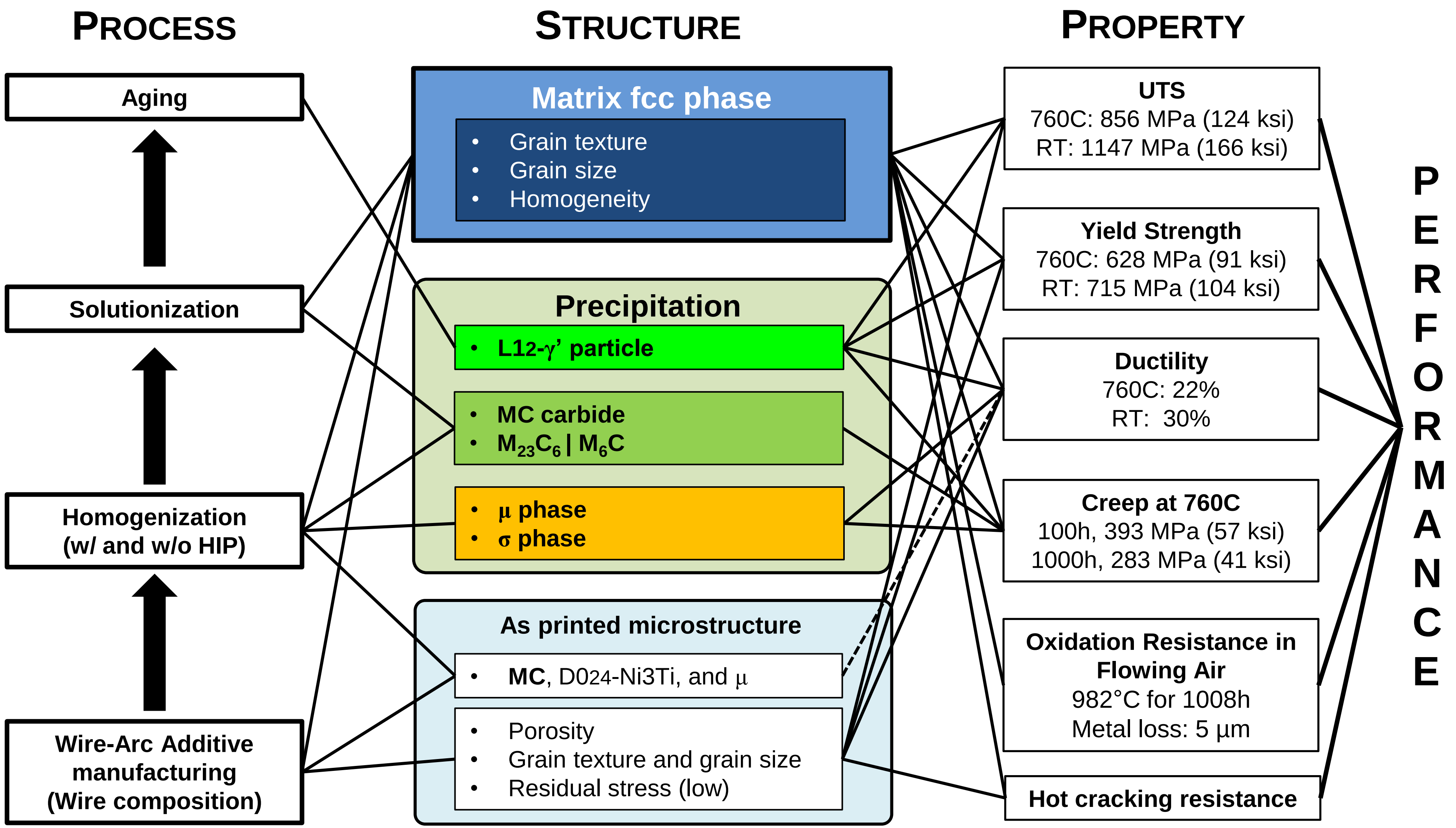




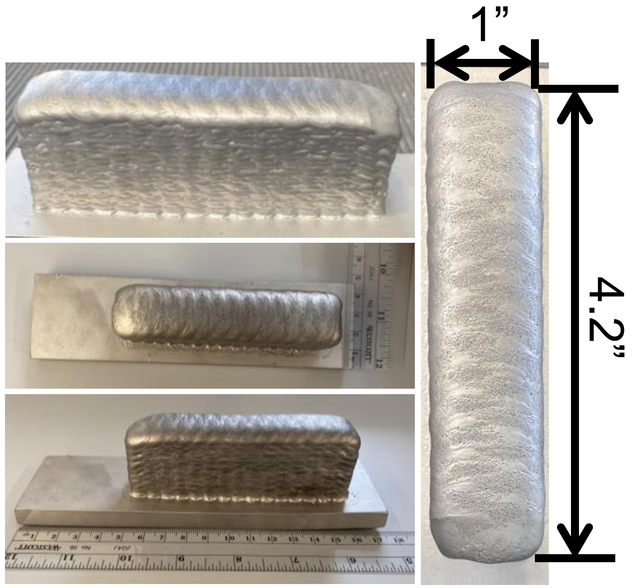
$$k_{Co}^{Ni} = 1, k_{Cr}^{In718} = 1.03, k_{Al}^{In718} = 1, k_{Ti}^{In718} = 0.69, k_{Mo}^{In718} = 0.82$$

Y. Yang, MICROSTRUCTURAL EVOLUTION IN CAST HAYNES 282 FOR APPLICATION IN ADVANCED POWER PLANTS.
A. Ramakrishnan, Microstructure and mechanical properties of direct laser metal deposited Haynes 282 superalloy, 2019

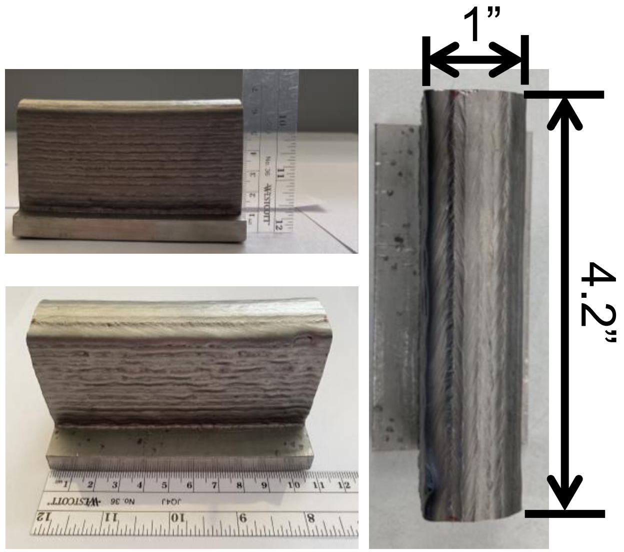
Systems Design Chart for Haynes 282



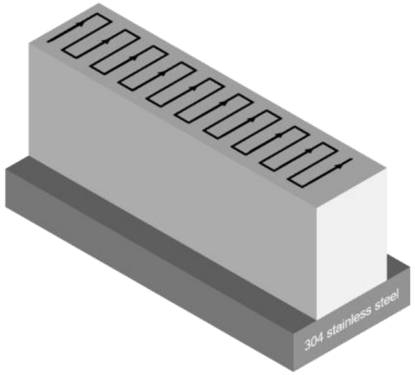
Printing strategy difference: Meander vs. Single Bead



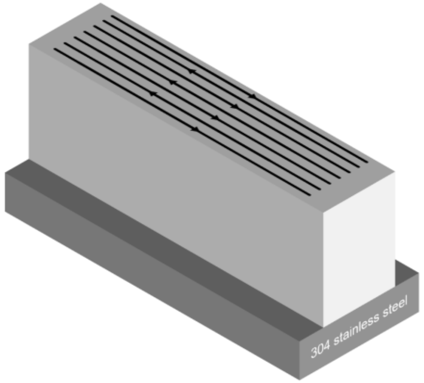
Multitrack Meander Haynes 282



Multitrack Single Bead Haynes 282

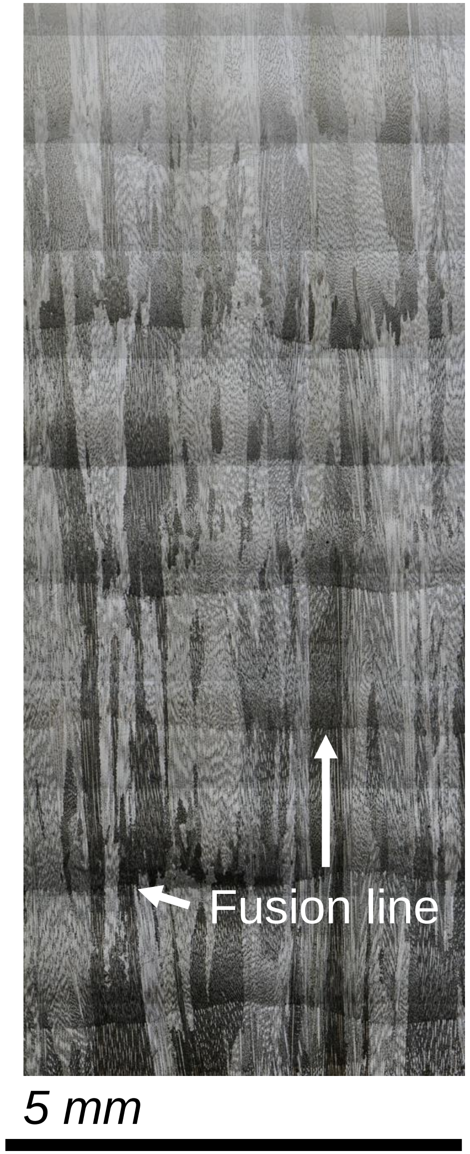


Zigzag, Meander



Single bead

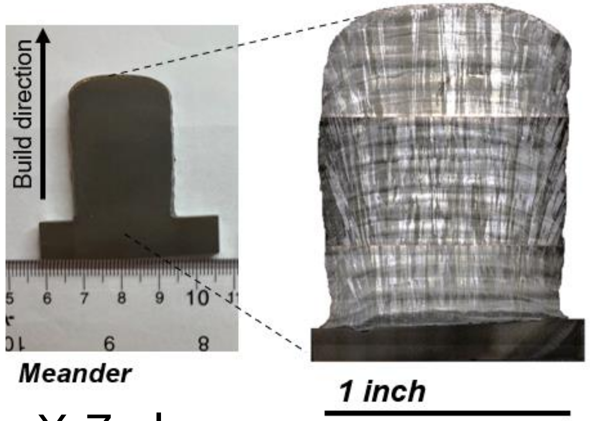
As-printed microstructure: Meander vs. Single Bead

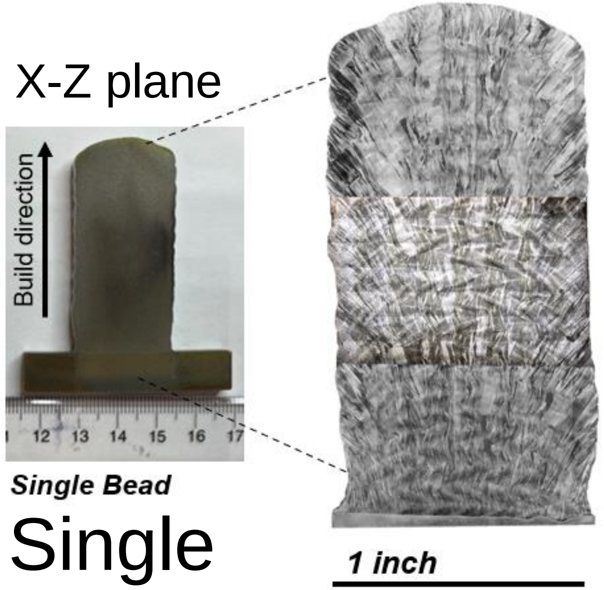


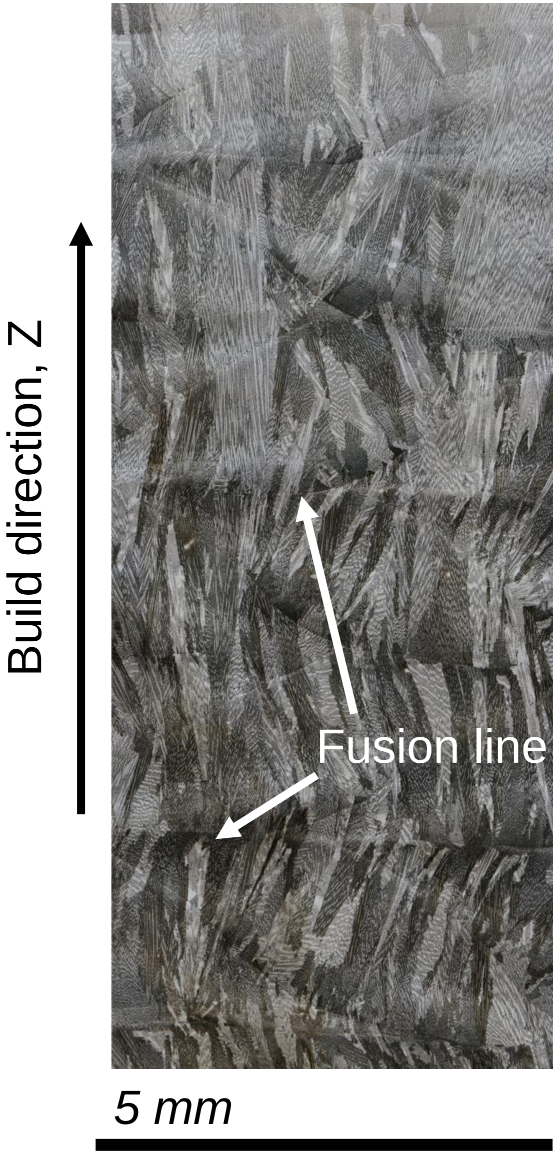
Zig-zag (meander)

vs.

Single bead

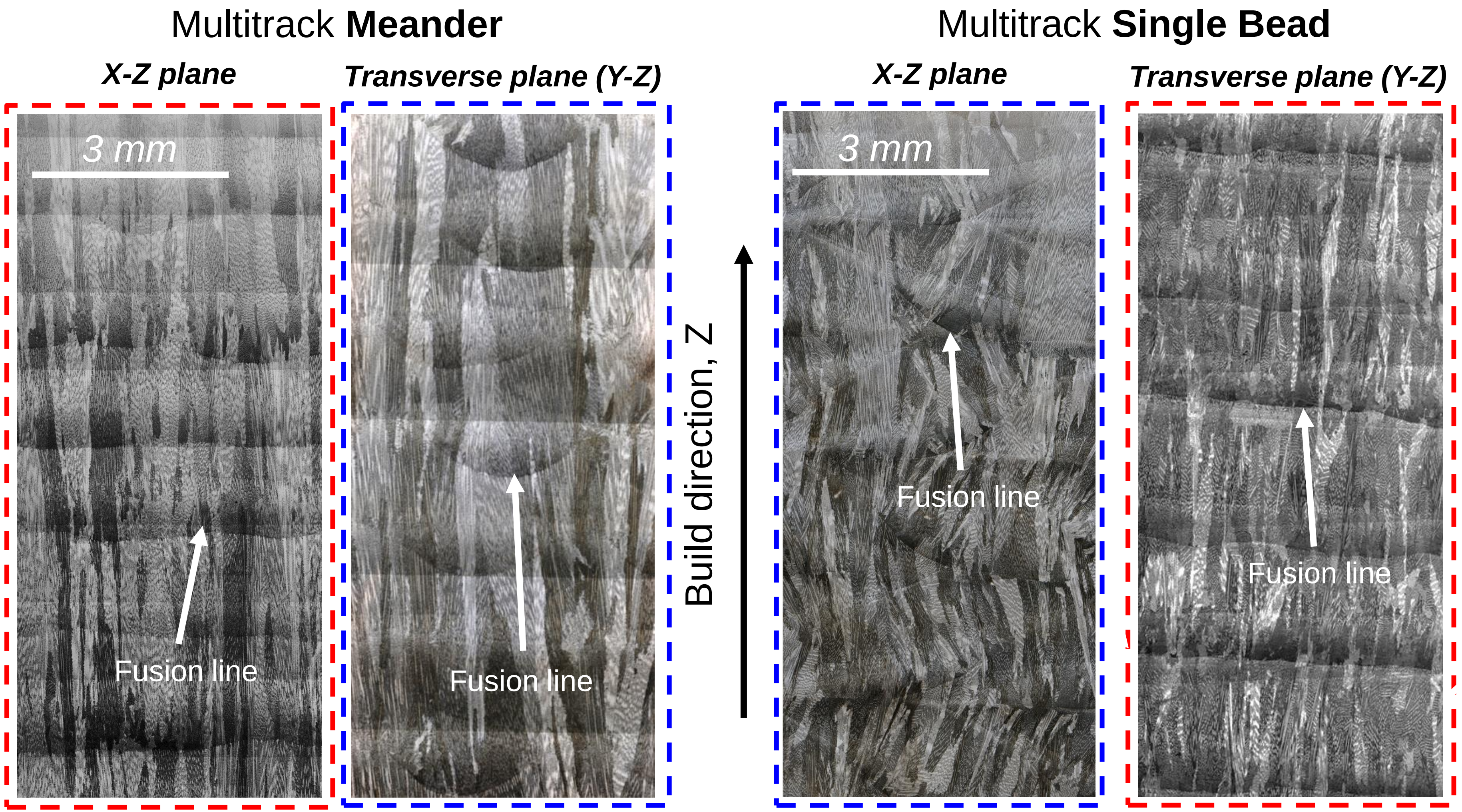






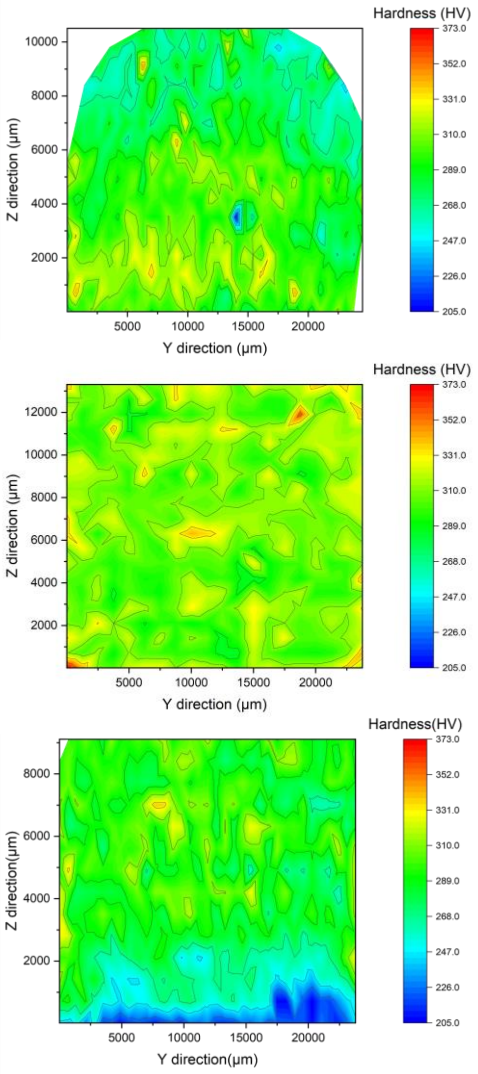
As-printed microstructure: Meander vs. Single Bead

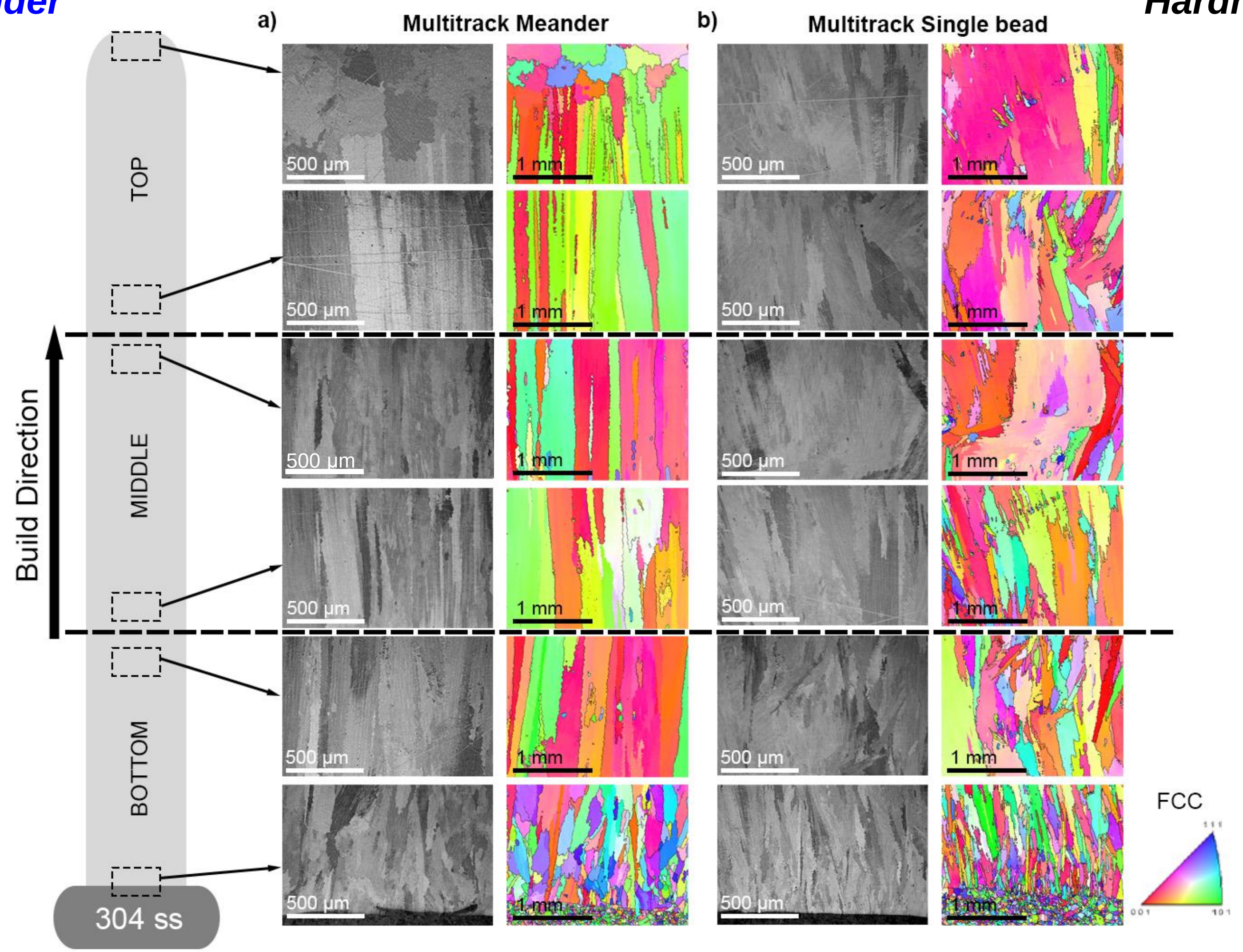
Similarities can be found between **X-Z plane of Meander** and **Y-Z (transverse) plane of Single bead**
Y-Z (transverse) plane of Meander and **X-Z plane of Single bead**



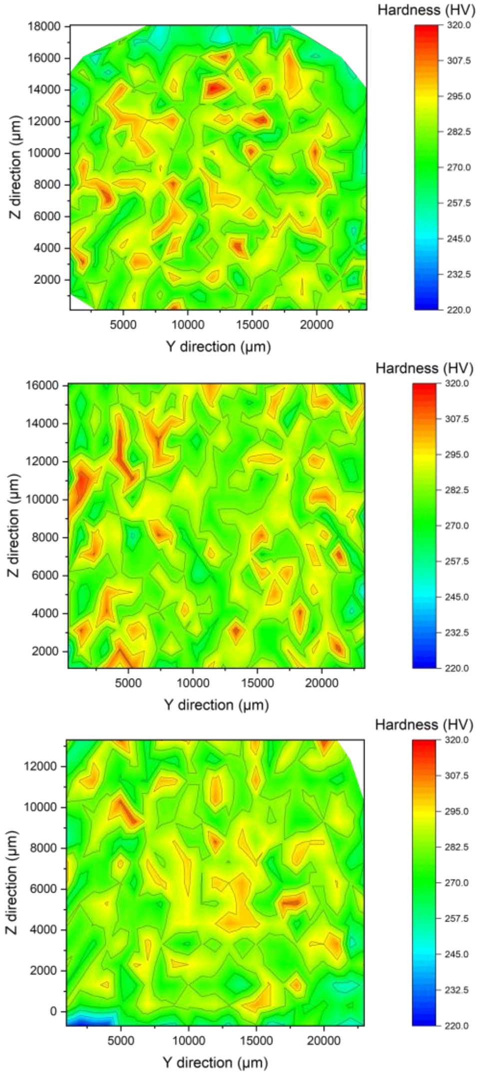
As-printed microstructure: Meander vs. Single Bead

Hardness Map of Meander





Hardness Map of Single Bead



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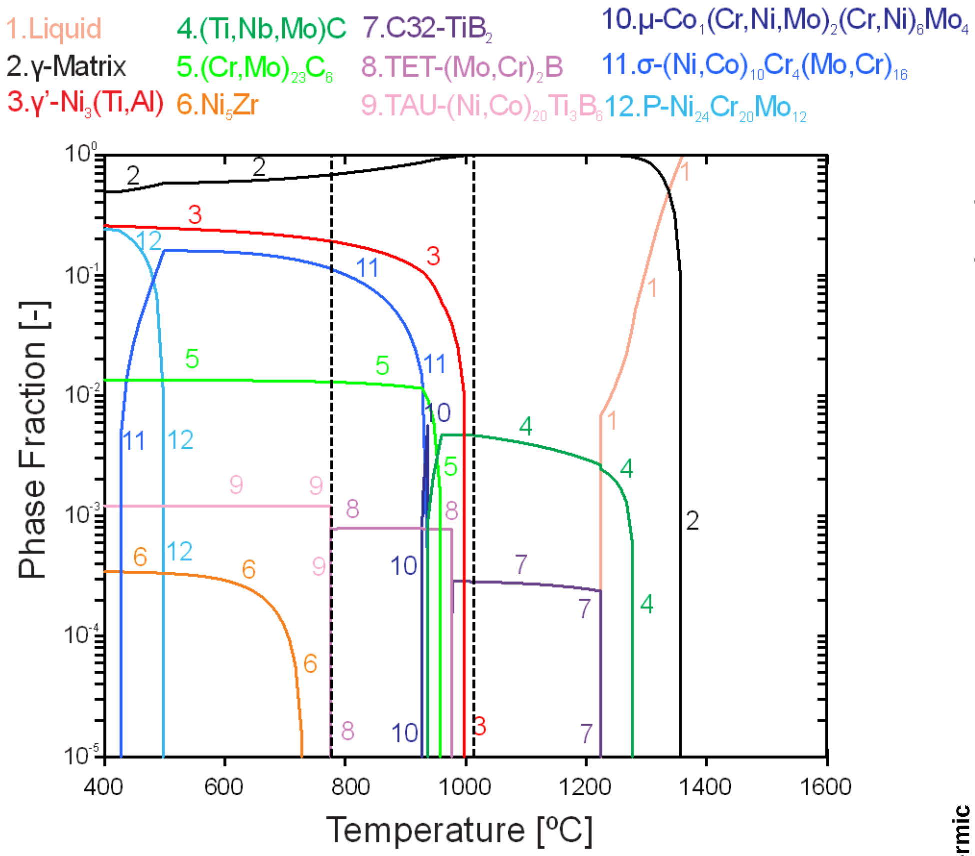
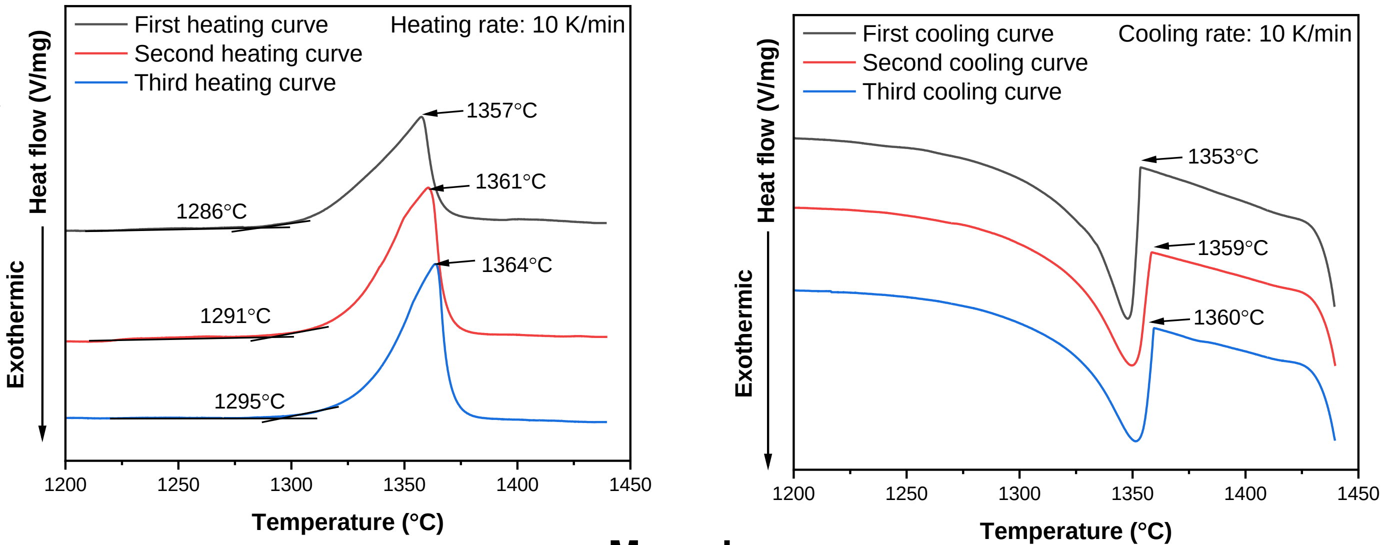
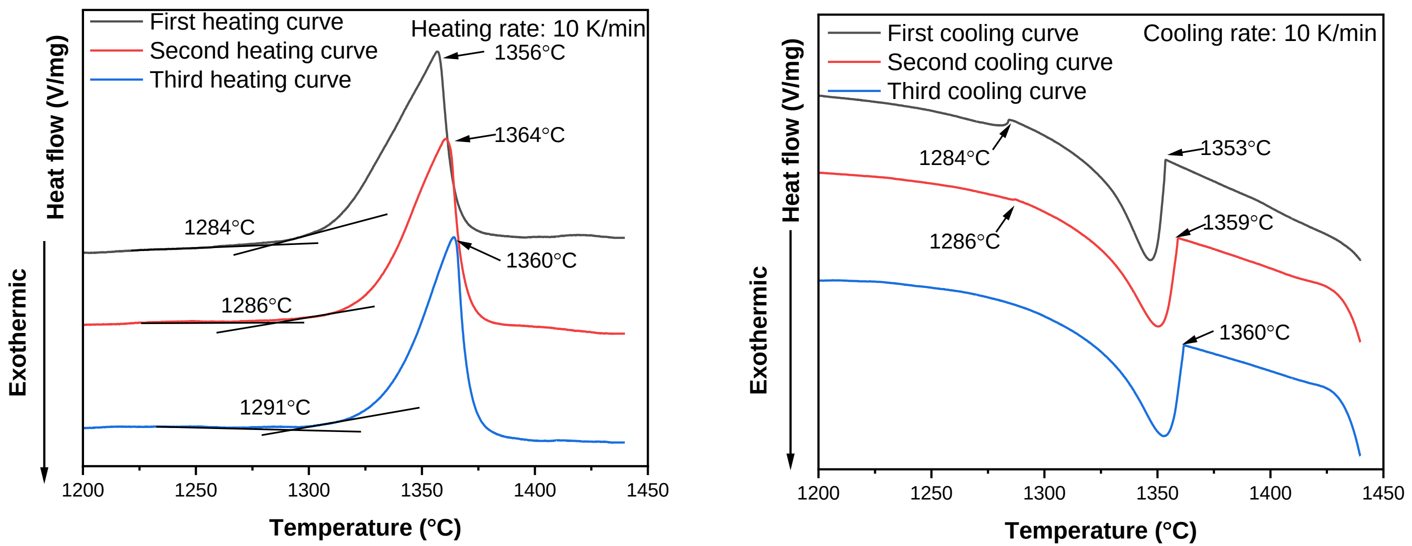
Determination of phase transformation temperature



Single-Bead



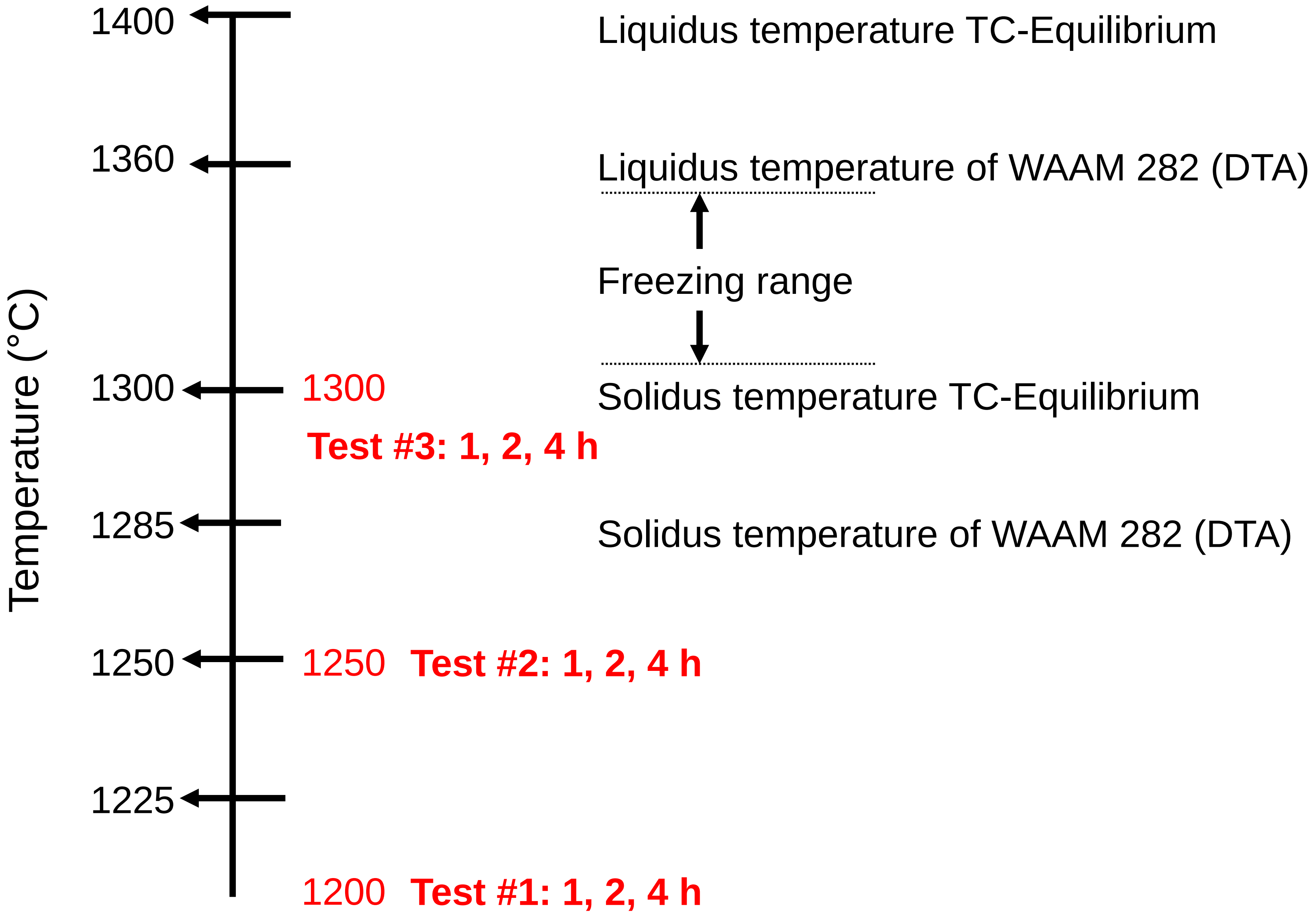
Meander



Determination of phase transformation temperature (cont'd)

Transformation temperature	CALPHAD prediction	Meander		Single bead	
		Heating (10 K/min)	Cooling (10 K/min)	Heating (10 K/min)	Cooling (10 K/min)
Solidus	1300 °C	1287.4 ± 3.6	1285.0 ± 1.4	1290.7 ± 4.5	NA
Liquidus	1400°C	1360.0 ± 4.0	1358.0 ± 4.6	1360.7 ± 3.5	1357.3 ± 3.8

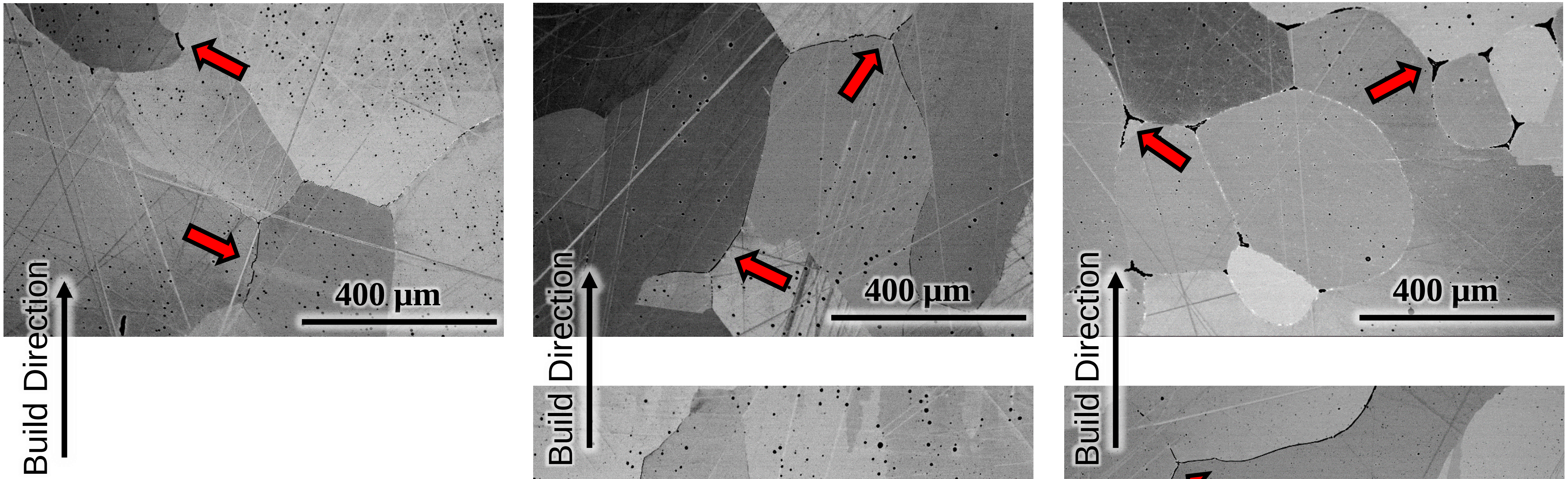
Recrystallization Study: Choice of temperatures

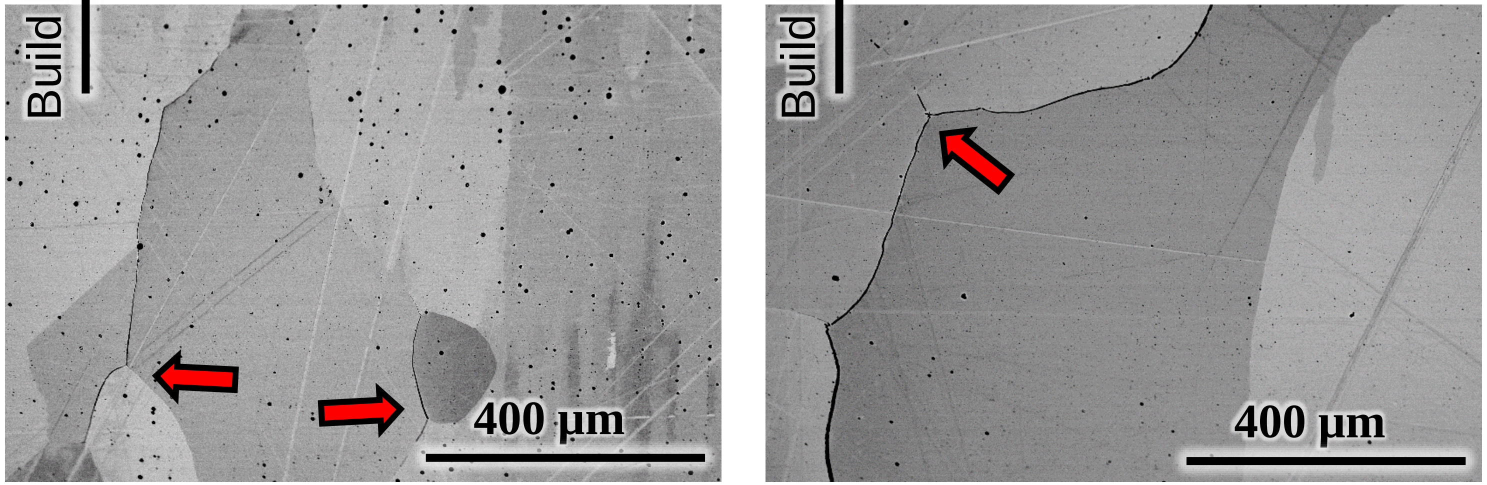


BSE-SEM micrographs after recrystallization at 1300°C – Initial Melting

200 x mag

	1 h	2 h	4 h
Multi-Track Single Bead			
Multi-Track Meander			





Heat treatment at 1300°C did not cause bulk melting, however, initial melting can be observed

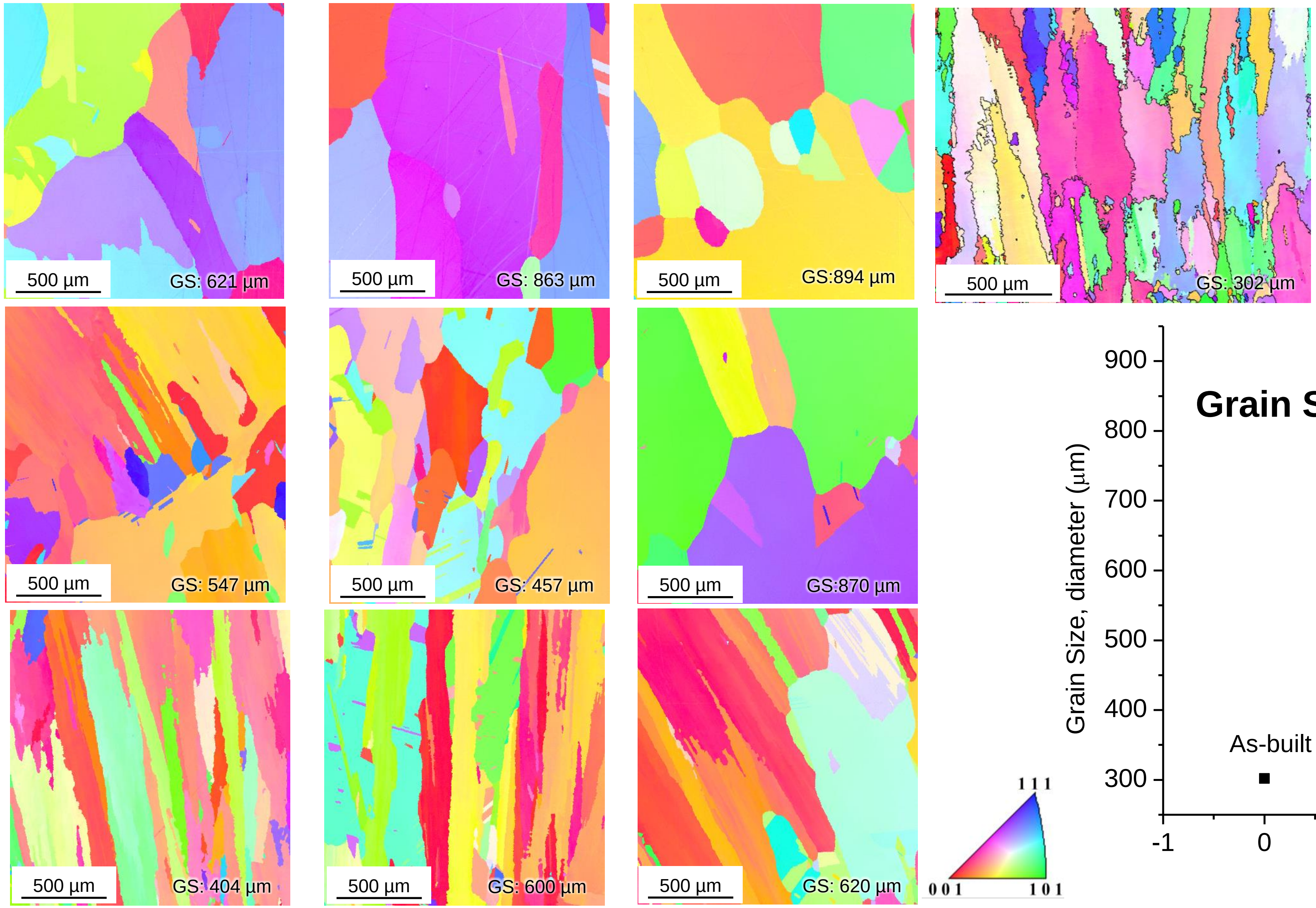
Recrystallization studies for build using Multi-Track **Single Bead**

1 h | 2 h | 4 h | As Built

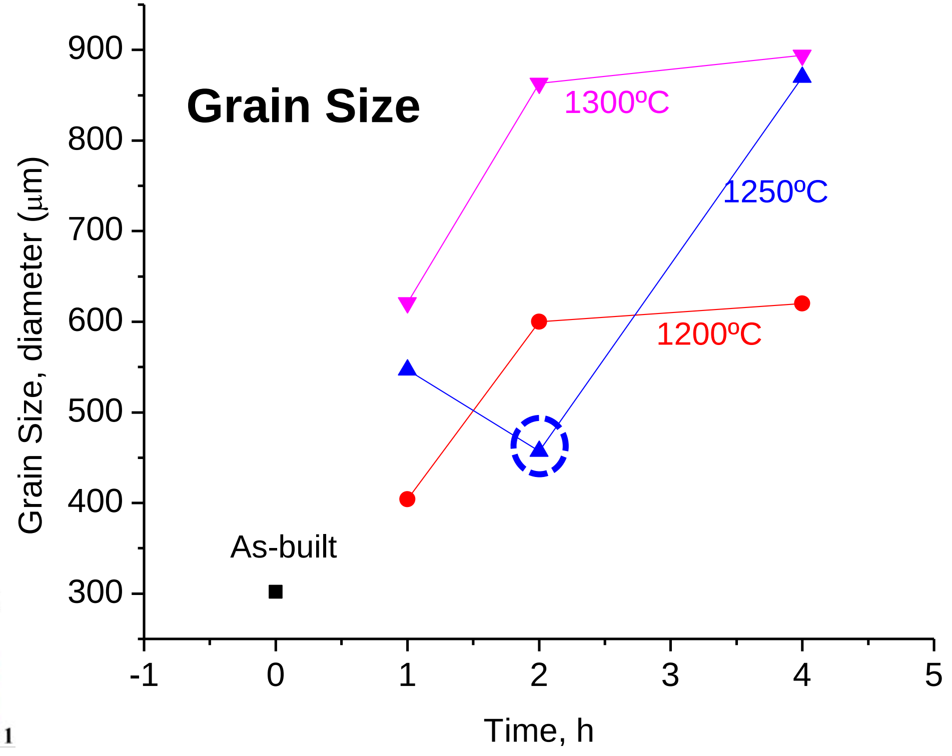
1300 °C

1250 °C

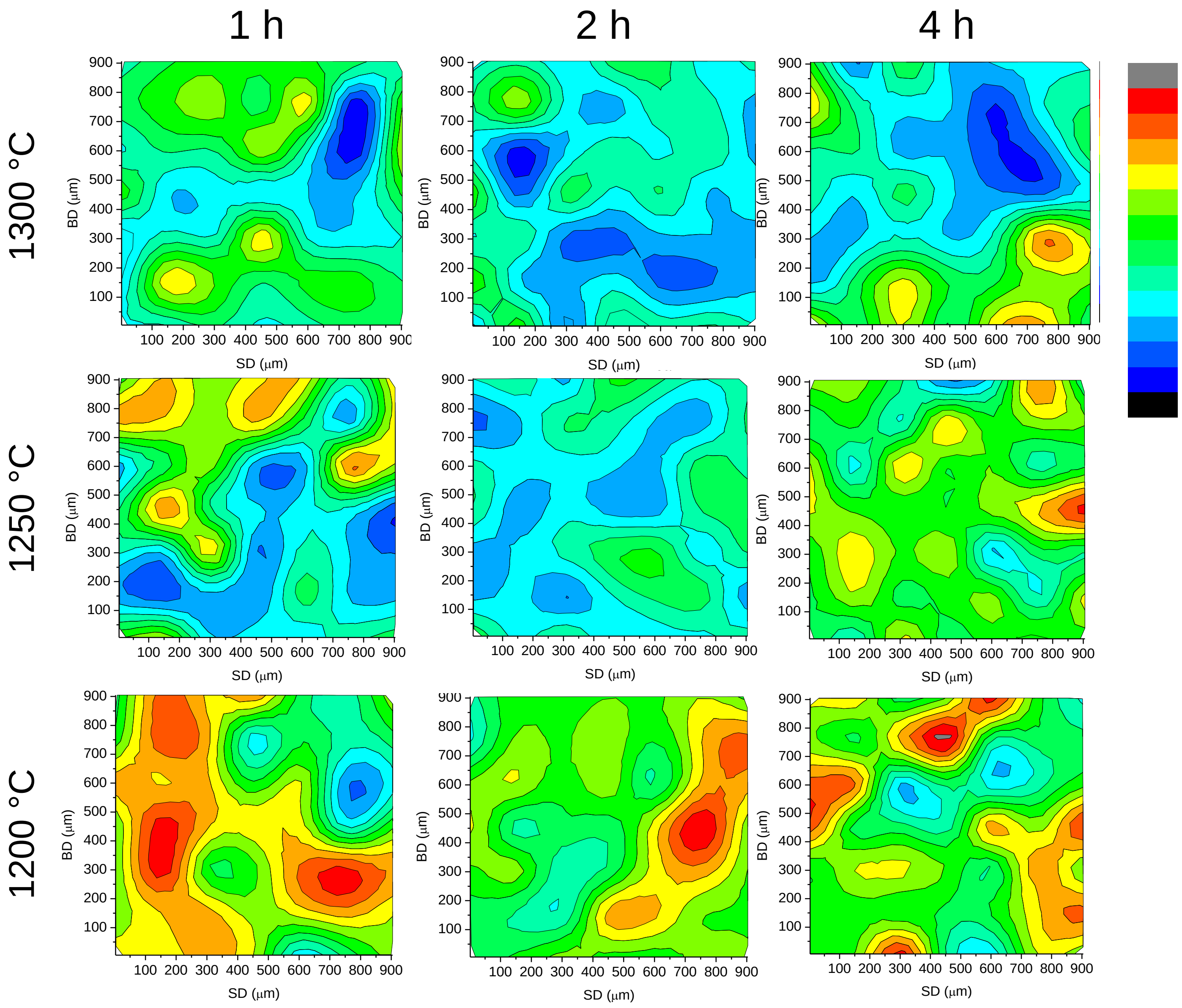
1200 °C

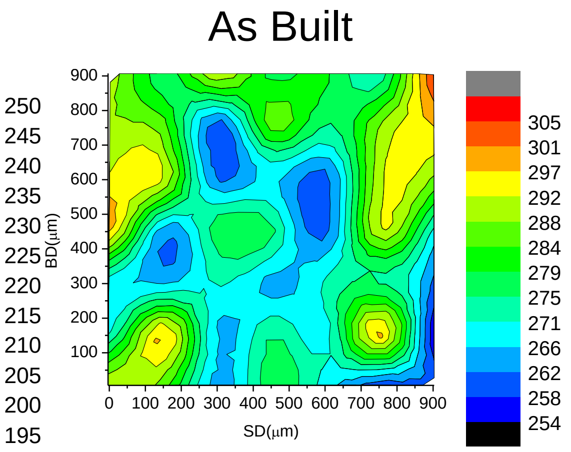


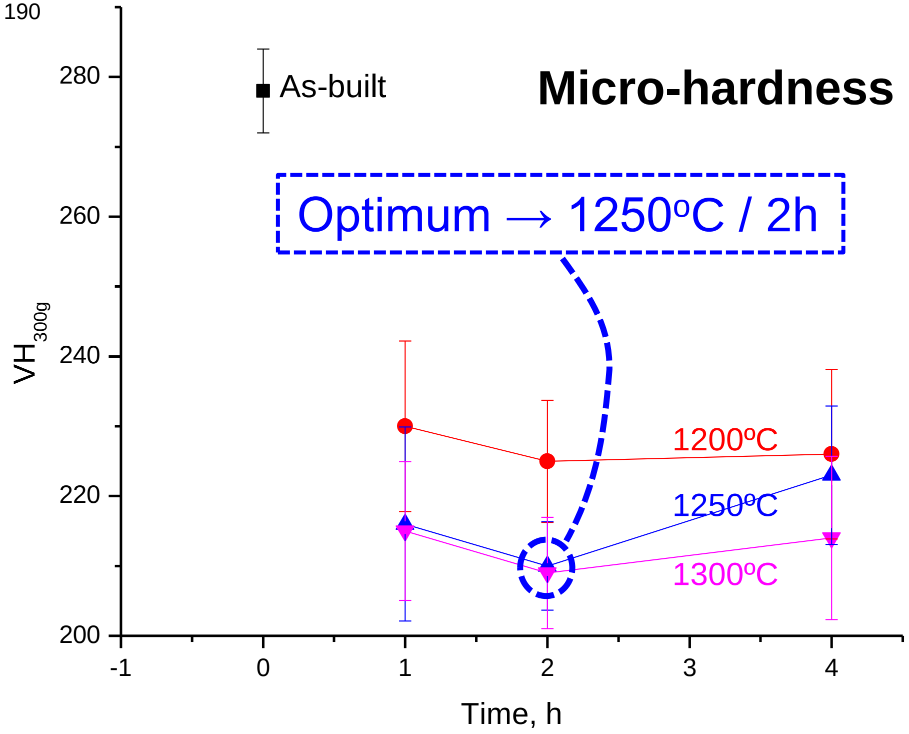
Signs of recrystallization observed at 1250°C 1-2h, and fully recrystallizes at 1250°C 4h



Recrystallization studies for build using Multi-Track **Single Bead, Hardness**







Summary of recrystallization studies

No.	Temperature [°C]	Time [h]	Single Bead		Meander	
			HV_{300g}	Std Dev	HV_{300g}	Std Dev
1	1200	1	230	12.2	220	6.8
2	1200	2	225	8.75	221	6.96
3	1200	4	226	12.14	214	5.64
4	1250	1	216	13.9	217	6.26
5	**1250**	**2**	**210**	**6.33**	**215**	**7.08**
6	1250	4	223	9.91	220	6.71
7	1300	1	215	9.91	223	8.03
8	1300	2	209	7.98	216	5.87
9	1300	4	214	11.69	209	6.28

⇨ Optimum

Outline

- Background
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- Grain structure modeling
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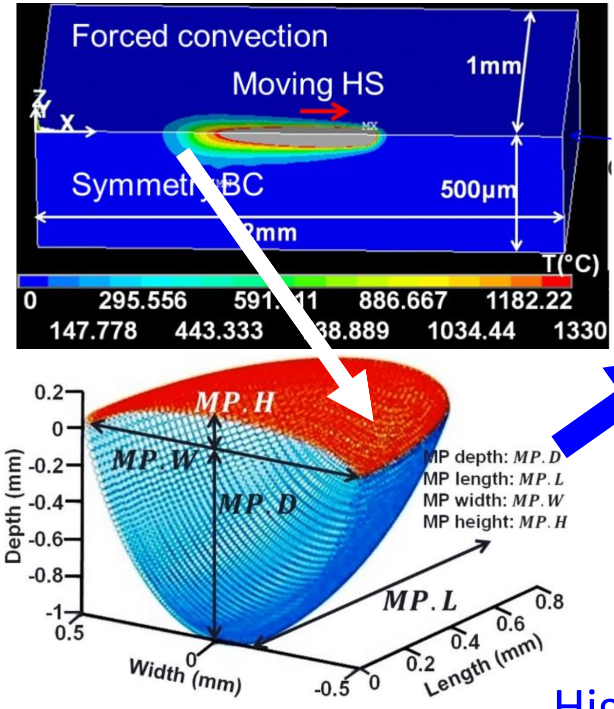
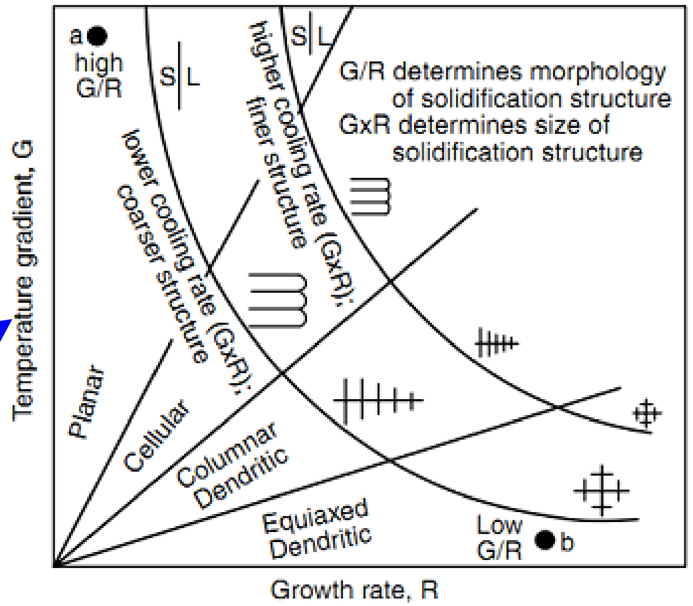
Discrete dendrite dynamics (DDD) model

Substrate and deposit → identical or almost identical lattice dimensions → Epitaxial dendrite growth

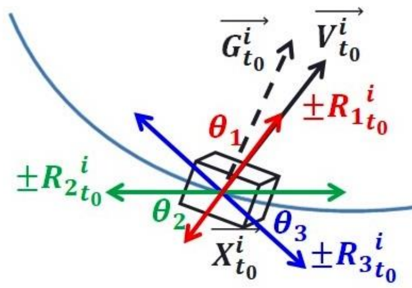
$$\Delta G^0_{nuc} \gg \Delta G^0_{epitaxy}$$



Discretized melt pool



High G at the S/L interface and a low growth rate (R) → high G/R → Epitaxial Growth



Initial melt pool (segment of ellipsoid)

$$\frac{x^2}{A^2} + \frac{y^2}{B^2} + \frac{(z - z_0)^2}{C^2} = 1 \quad (z \le 0)$$

$\pm R_{j\,t_0}^{\;i}$: Easy growth < 100 >directions for FCC/BCC crystals

$\overrightarrow{G^i_{t_0}}$: Local thermal gradient at $\overrightarrow{X^i_{t_0}}$

$\theta_{j=1,2,3}$: Angle between $\overrightarrow{G^i_{t_0}}$ and $\pm R_{j\,t_0}^{\;i}$, $\theta_1 = min(\theta_{j=1,2,3})$

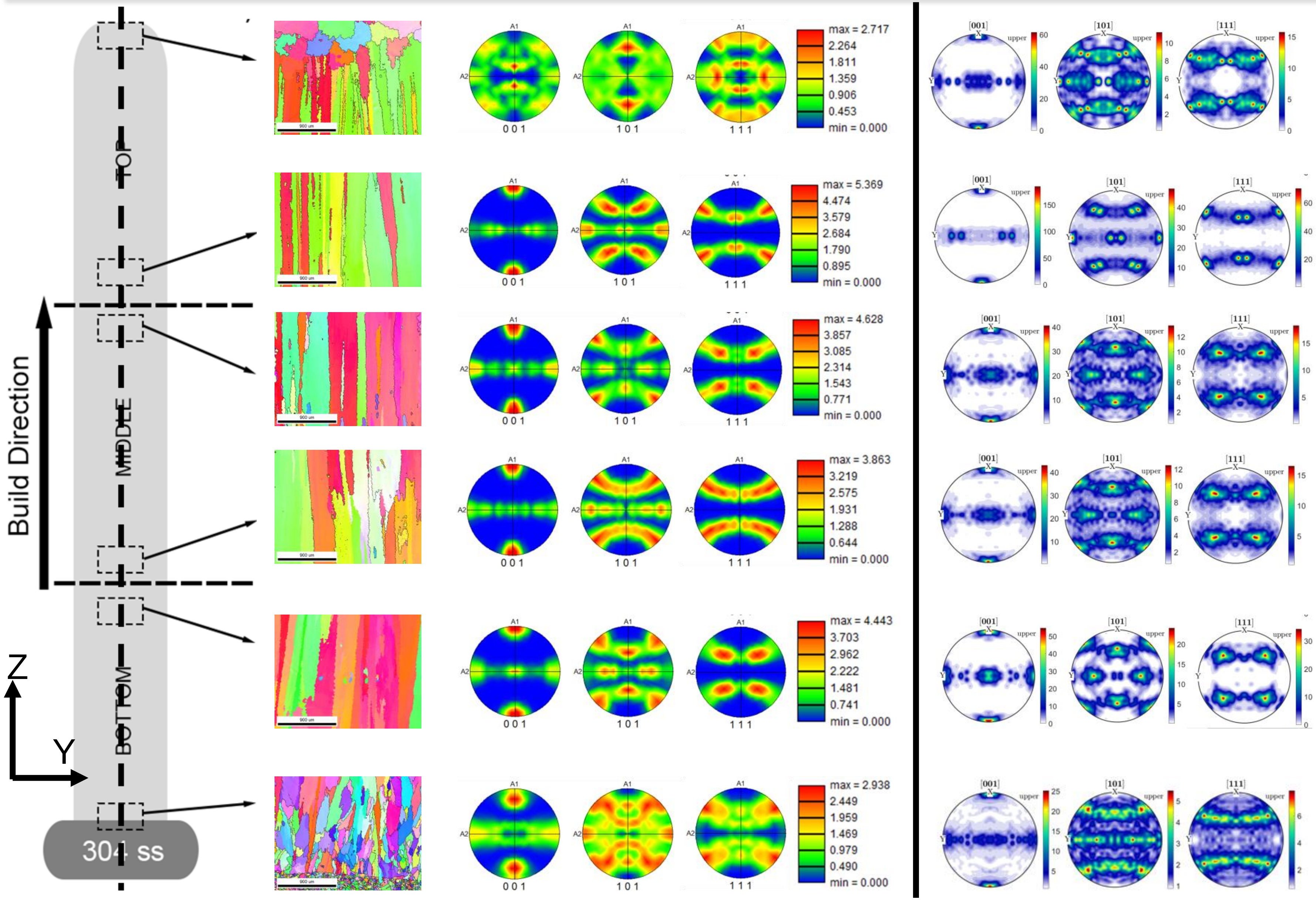
$\overrightarrow{V^i_{t_0}}$: Growth direction of the primary dendrite arm along θ_1

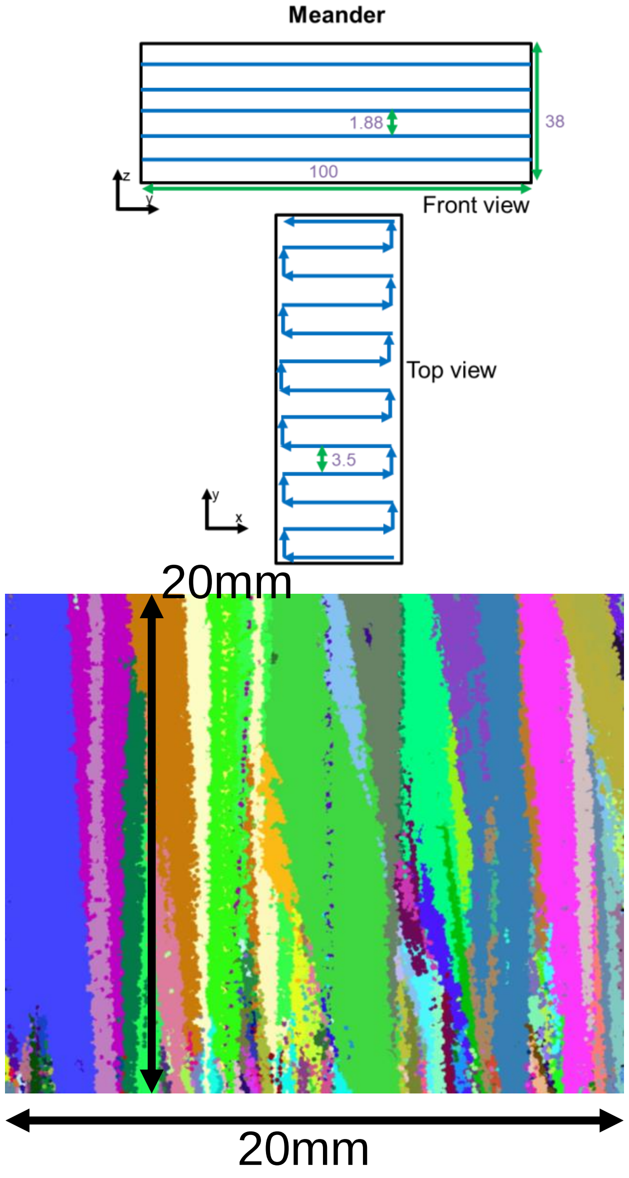
θ_2, θ_3: Possible secondary dendrite arm growth direction

Primary dendrite growth

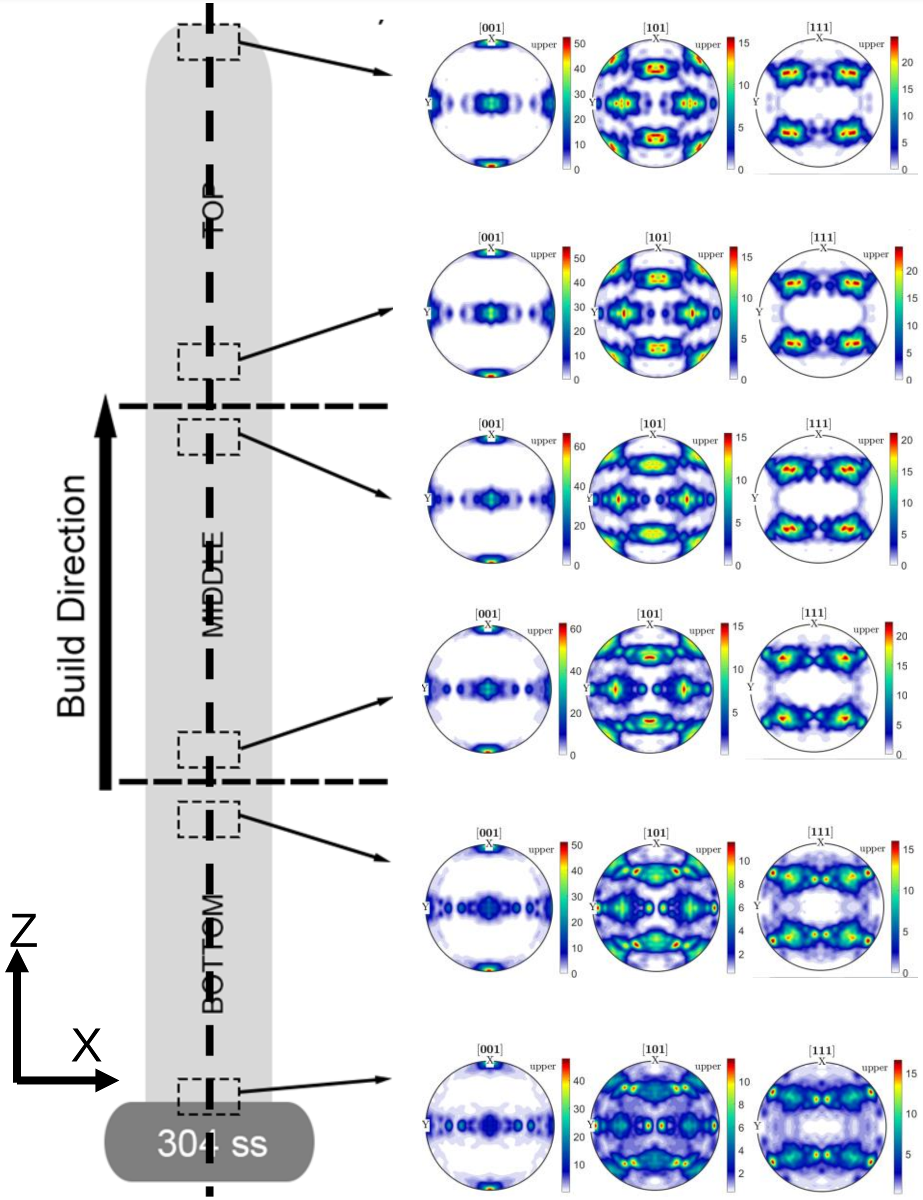
Paul, S., et. al., *A Discrete Dendrite Dynamics Model for Epitaxial Columnar Grain Growth in Metal Additive Manufacturing with Application to Inconel. Additive Manufacturing,* 2020. 36 pp. 101611

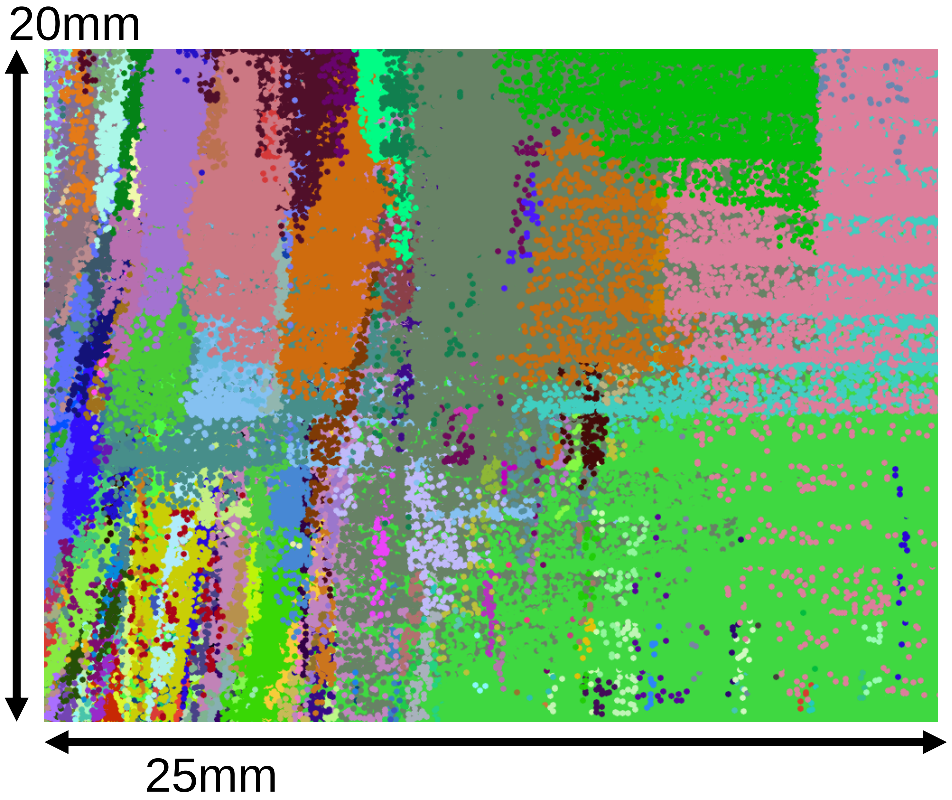
Meander (Longitudinal)-Calibration



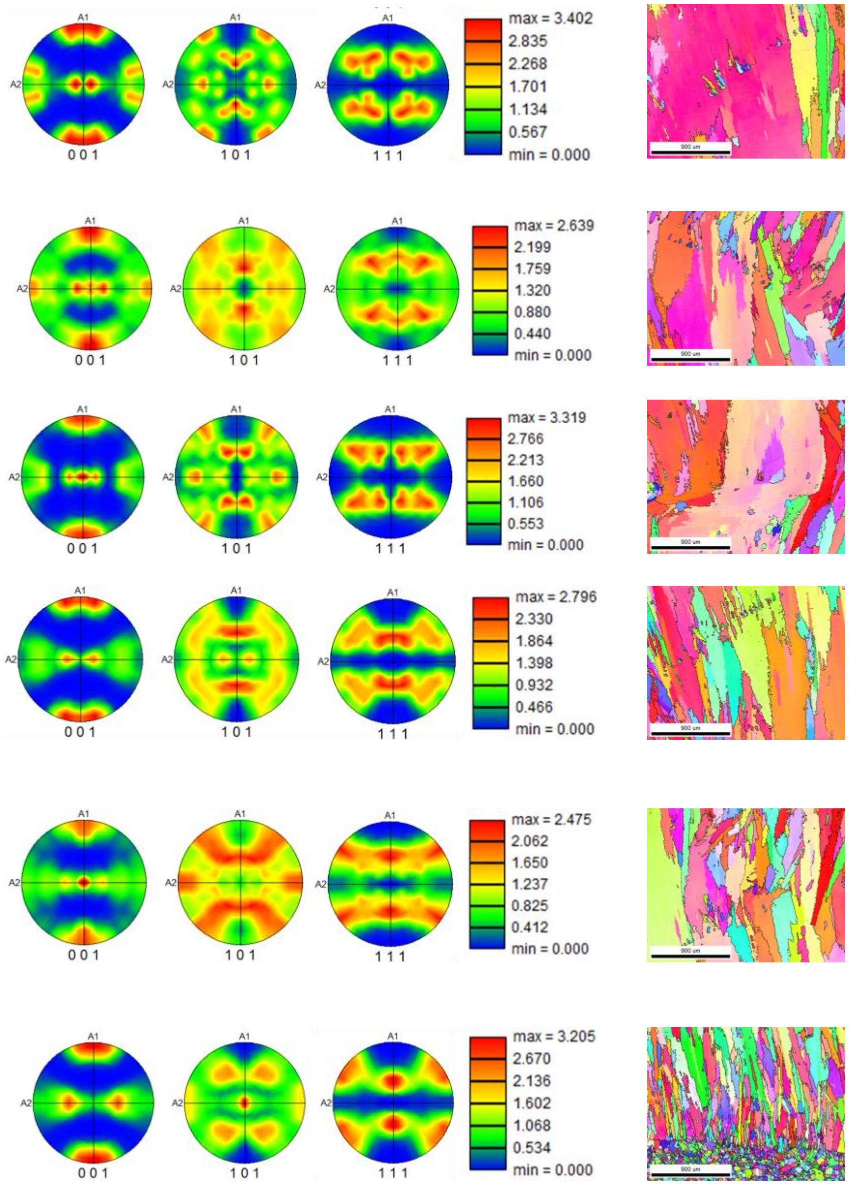


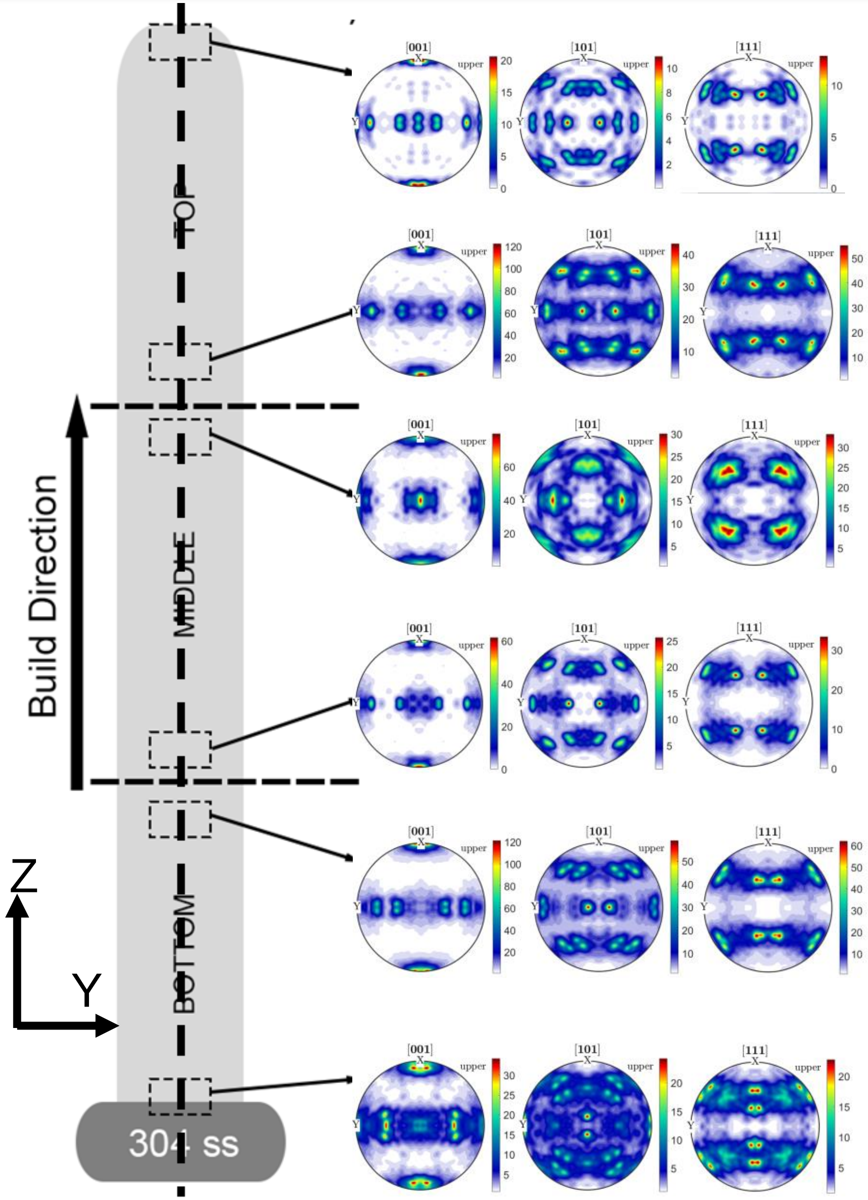
Meander (Transverse)-Validation

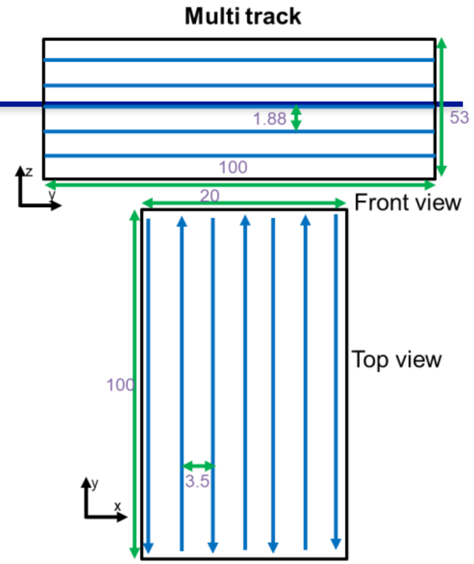


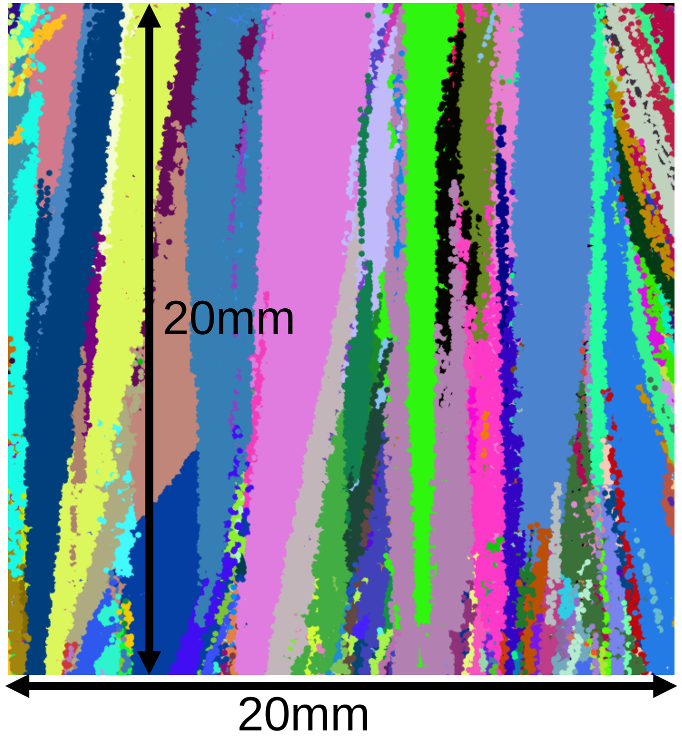


Multitrack (Longitudinal)-Calibration

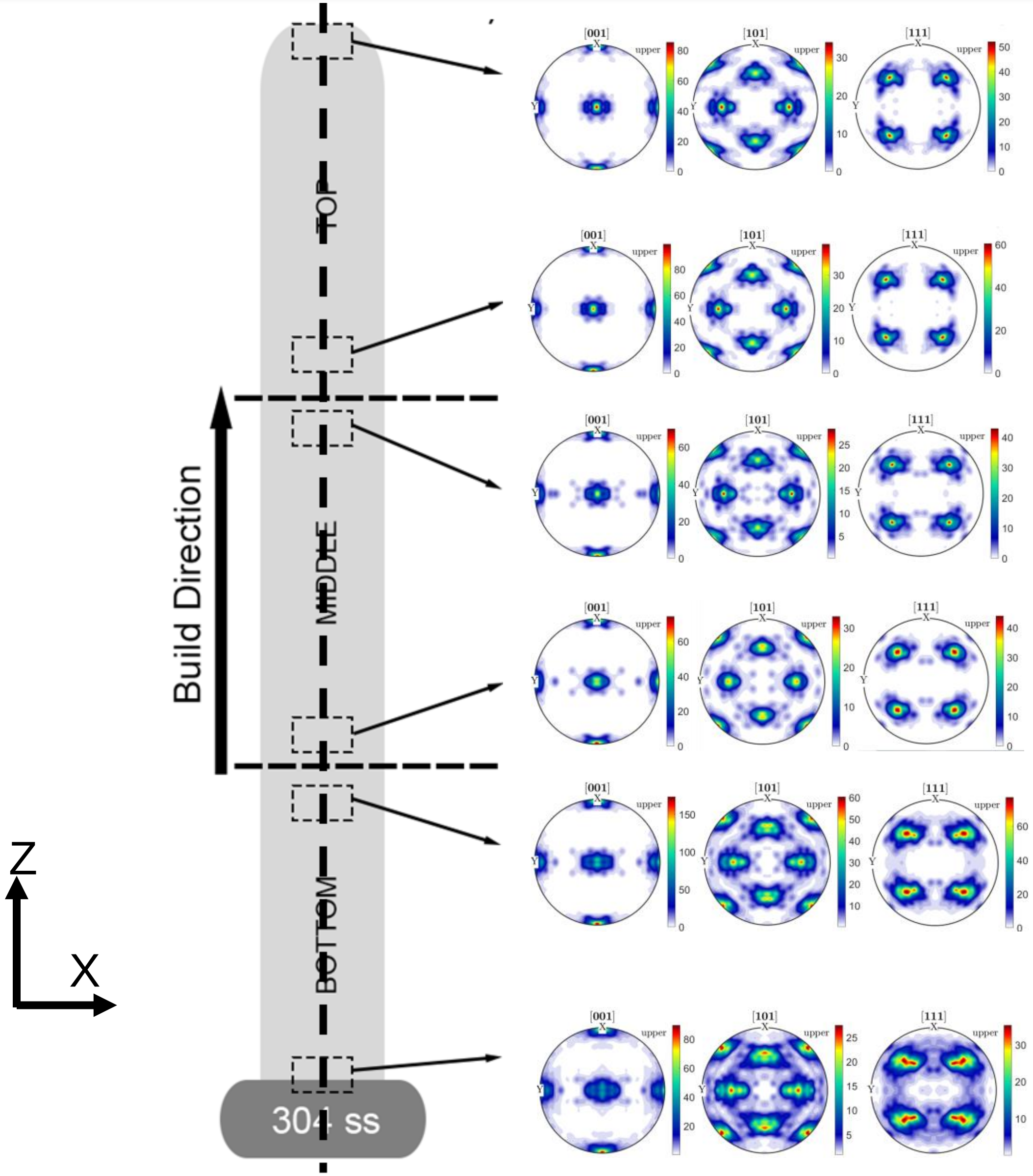


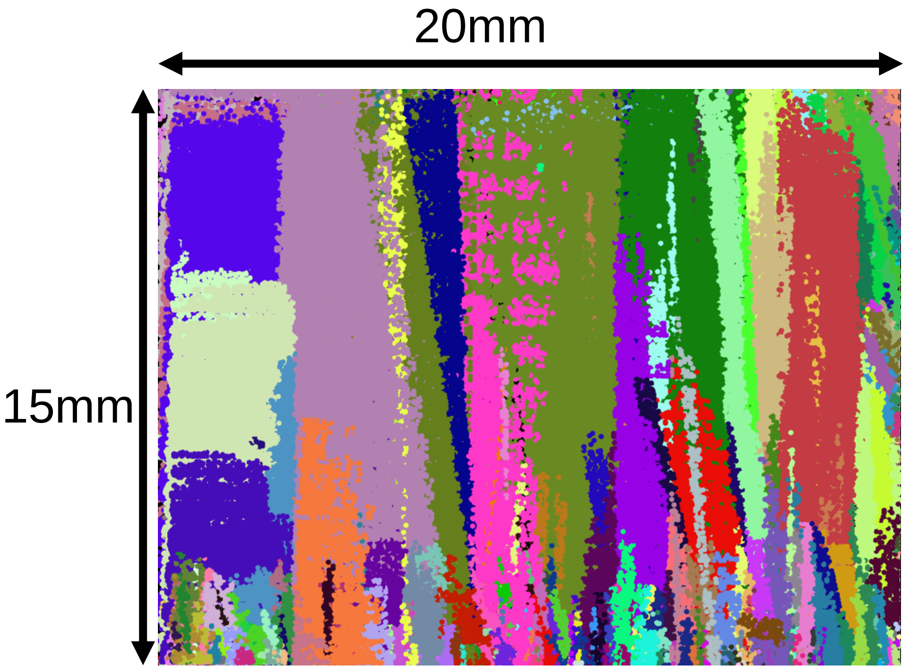






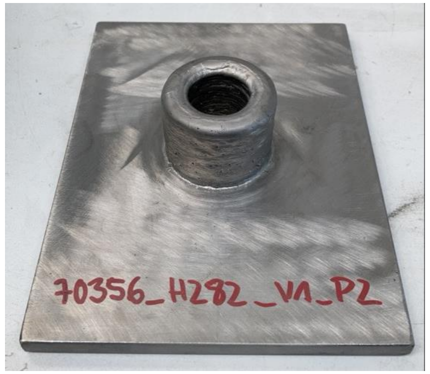
Multitrack (Transverse)-Validation

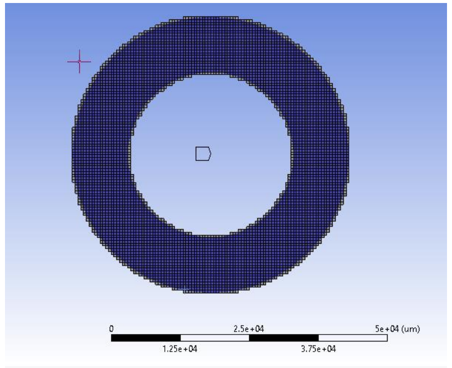


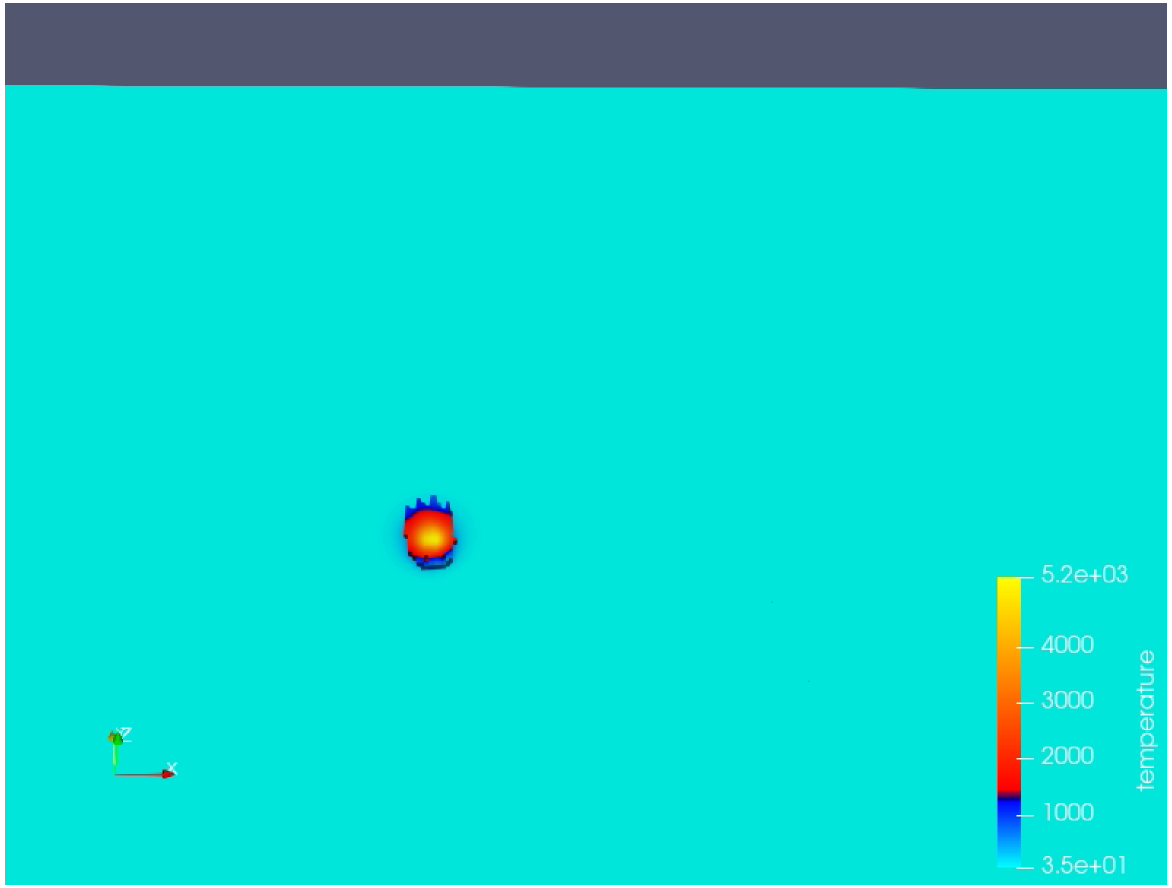


Process Simulation

- Haynes 282 parameters
- Cylinder of 22 layers
- Mesh size: 500 microns
- Meshing time: 40 min
- Preprocessing time: 15 min
- Simulation time:
  - 2 hours for thermal
  - 29 hours for thermomechanical

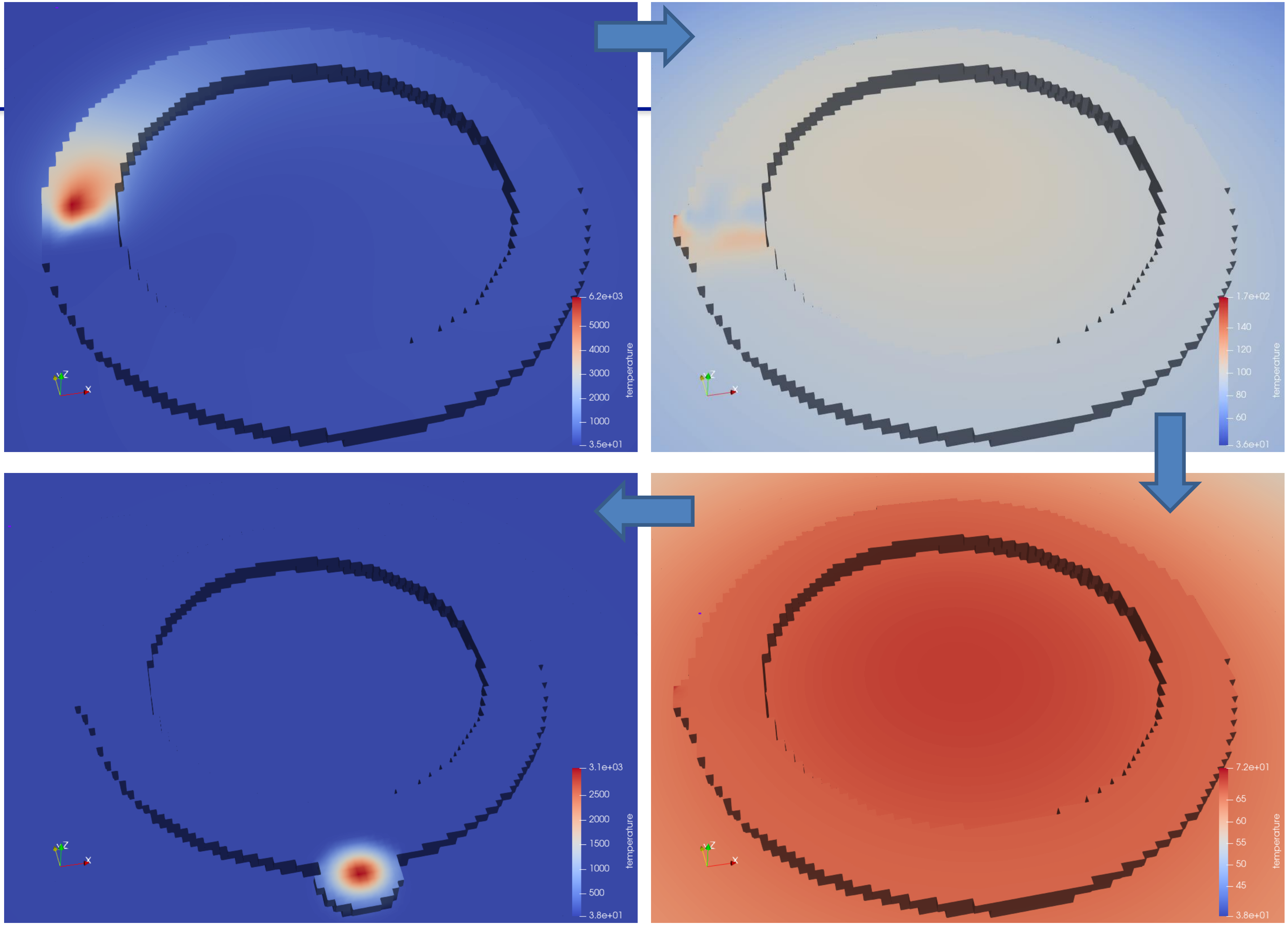






Weld cooling time

- Cooling time can be adjusted on a weld by weld basis
- Cooling time: ~60 seconds



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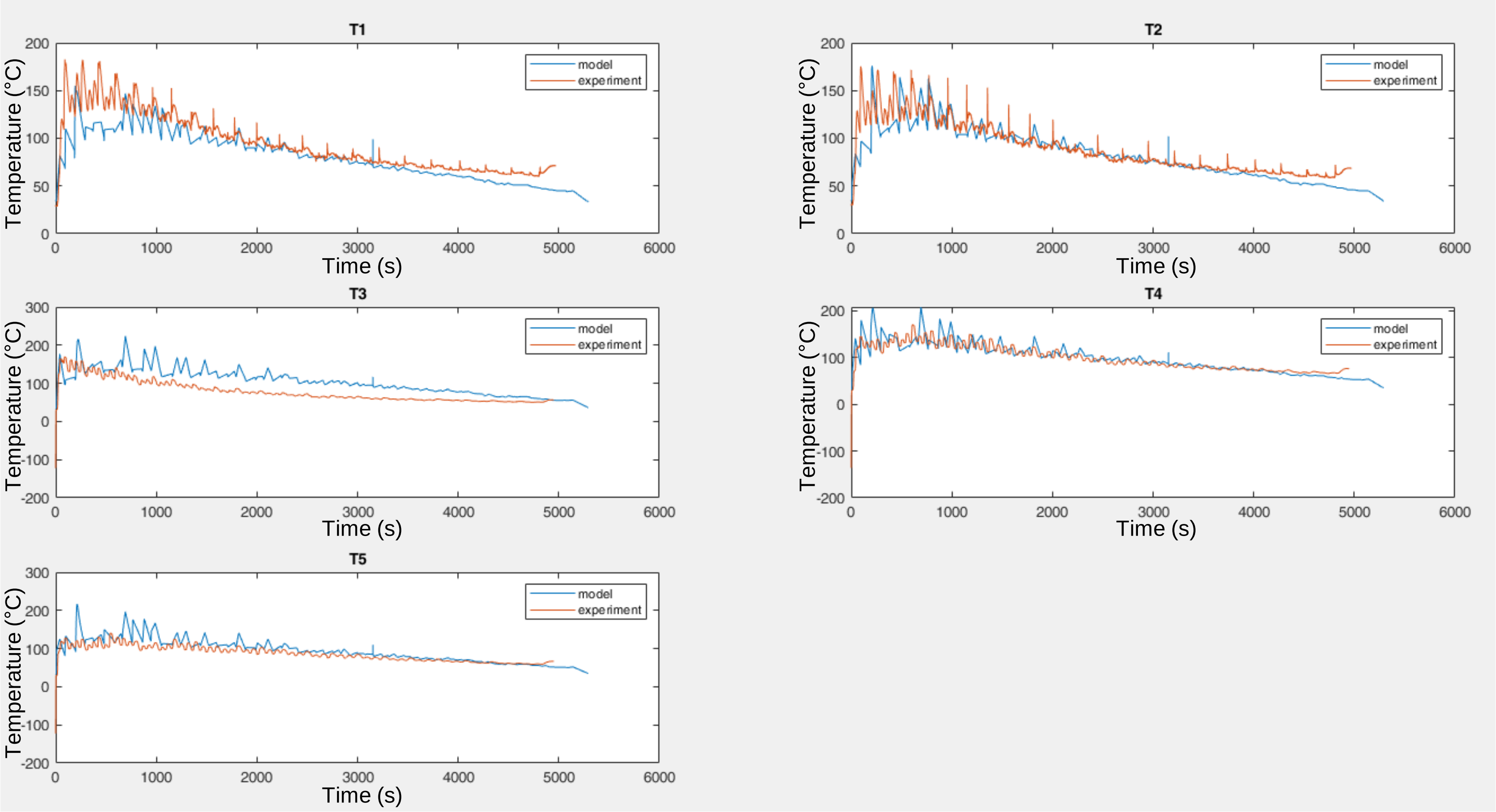
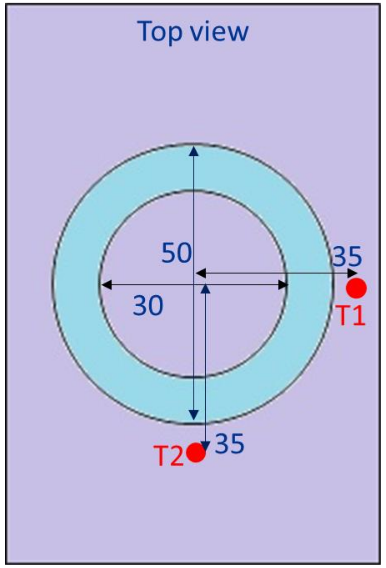
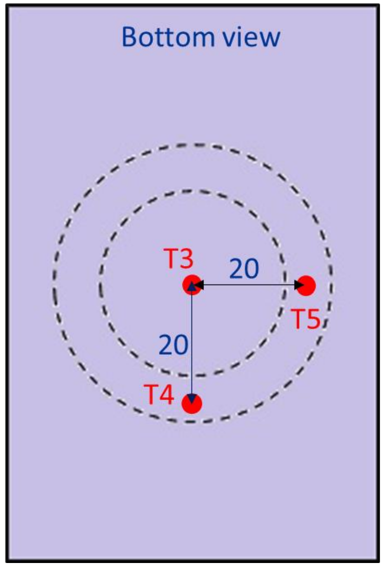
PITT | SWANSON ENGINEERING

Comparison against thermocouple data







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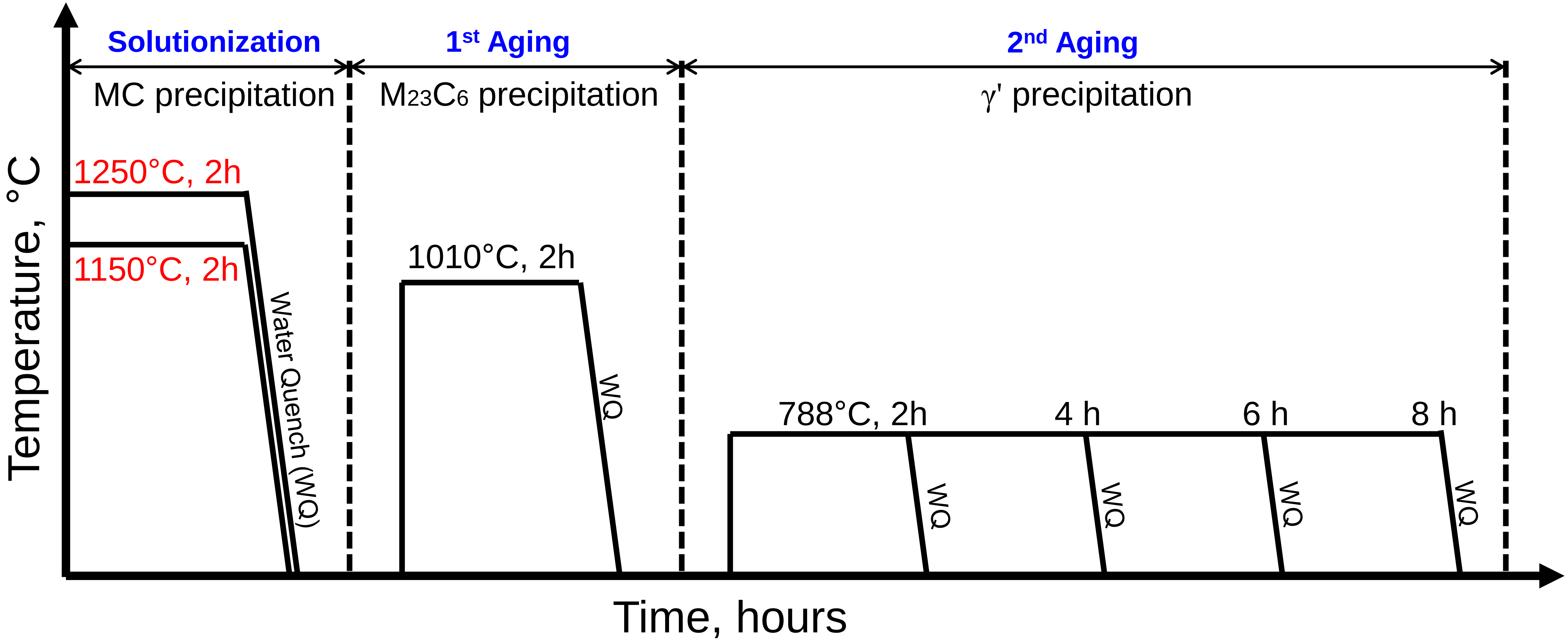
Precipitation strengthening study for calibration of precipitation simulation

Characterization methods

- Precipitate type
- Grain Structure
- Hardness

- Precipitate type
- Hardness

- γ' Size and distribution
- Hardness
- Tensile Test*

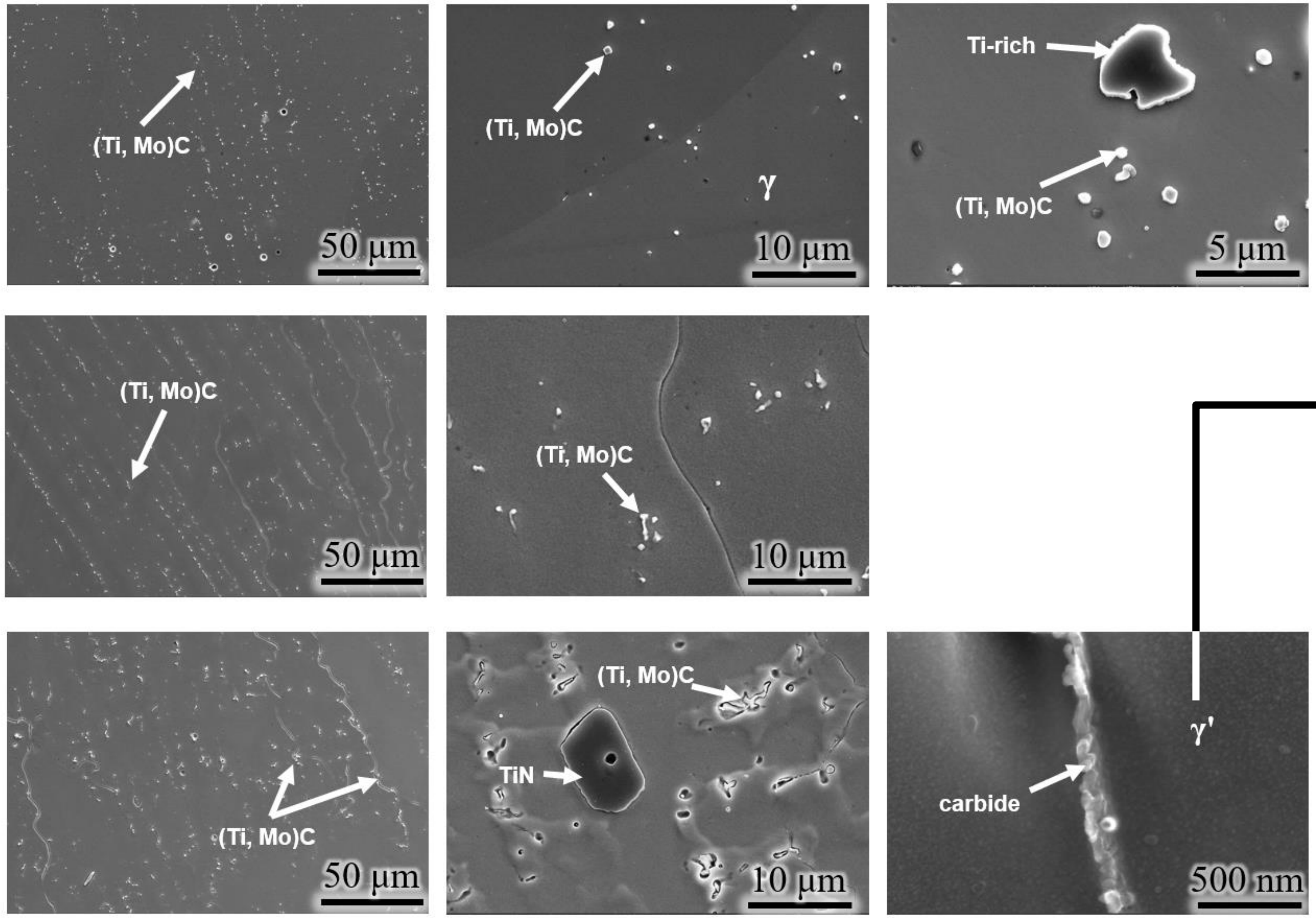


Solutionization – Phase stability

1250°C/2h

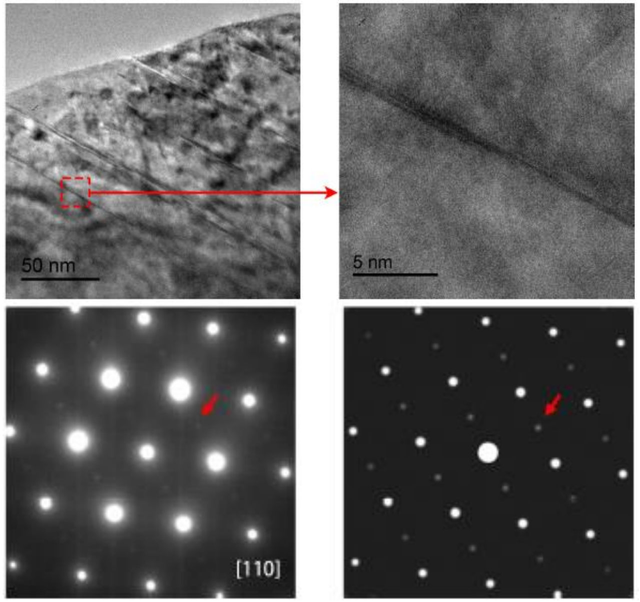
1150°C/2h

As-built



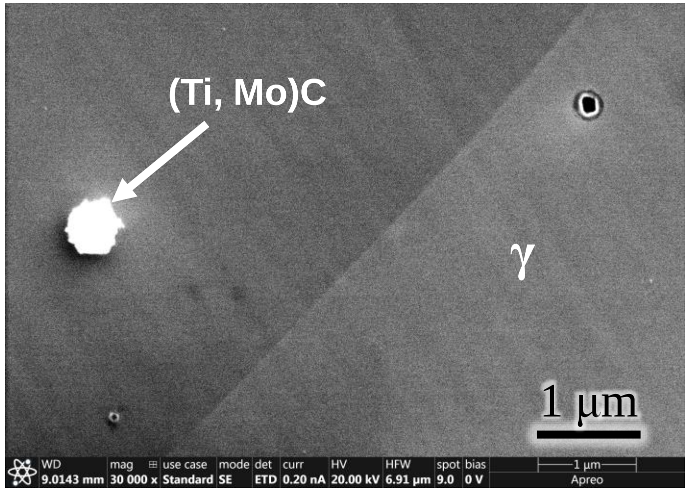
Lower Magnification Higher

γ’ observation in as-printed microstructure

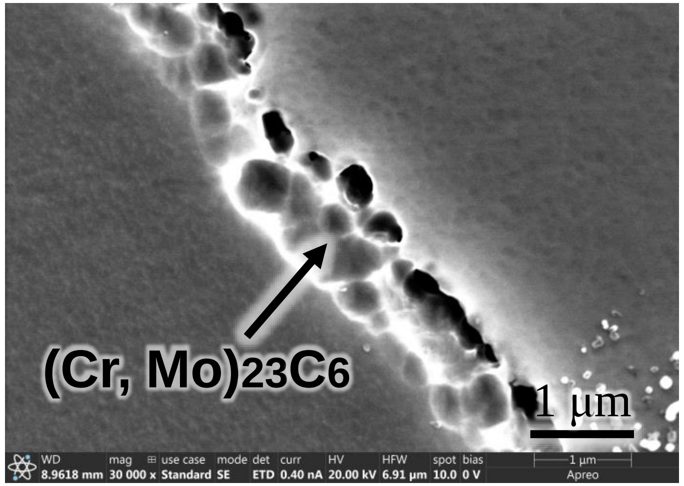


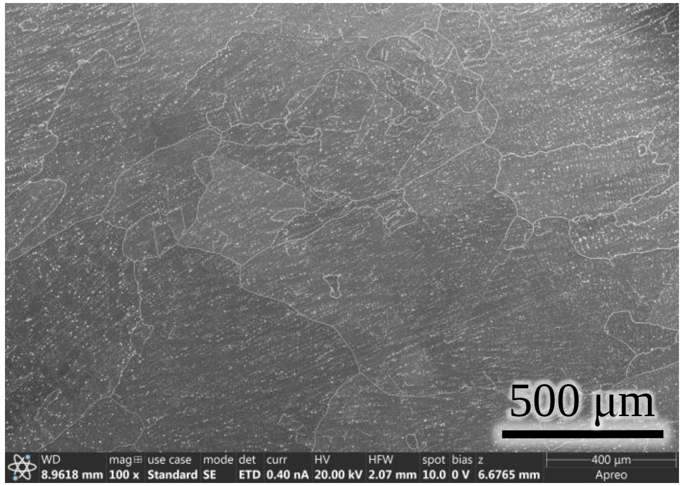
Solutionization & 1st Aging – Phase stability

1250°C/2h

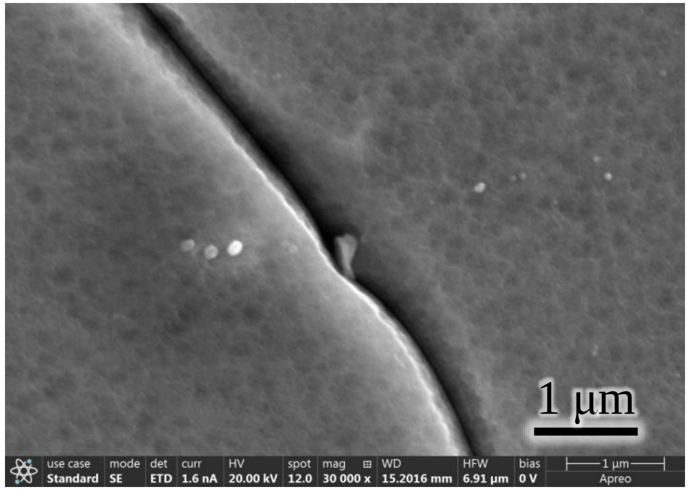


1250°C/2h + 1010°C/2h

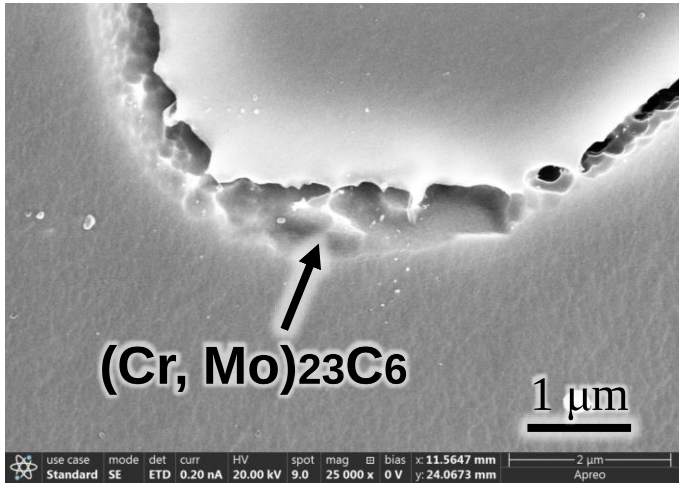


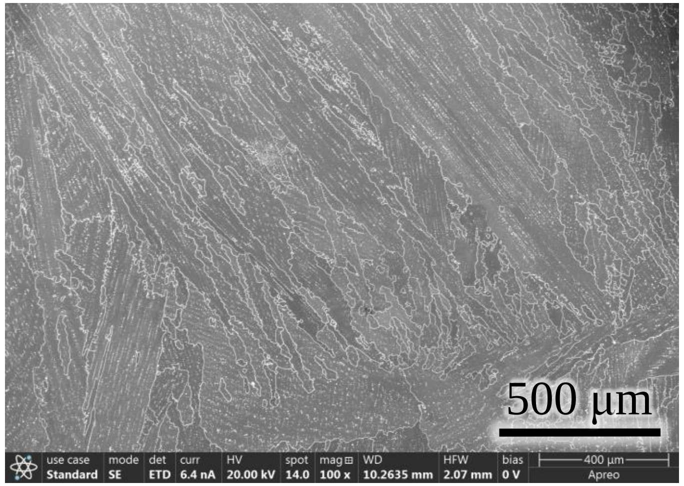


1150°C/2h



1150°C/2h + 1010°C/2h

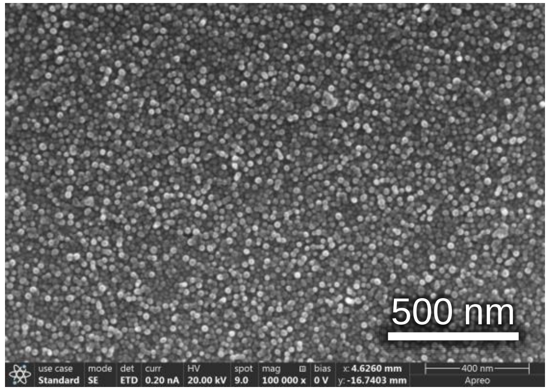




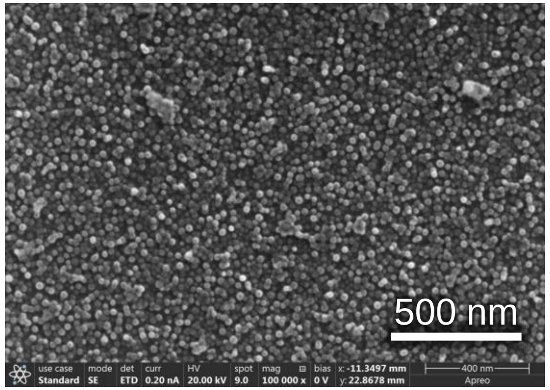
2nd Aging – γ' precipitation

1250°C/2h + 1010°C/2h + 788°C/*x*h

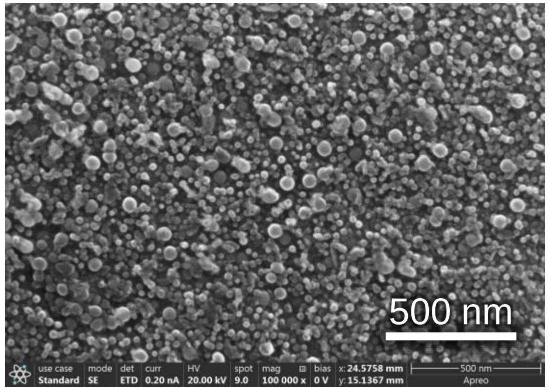
2h



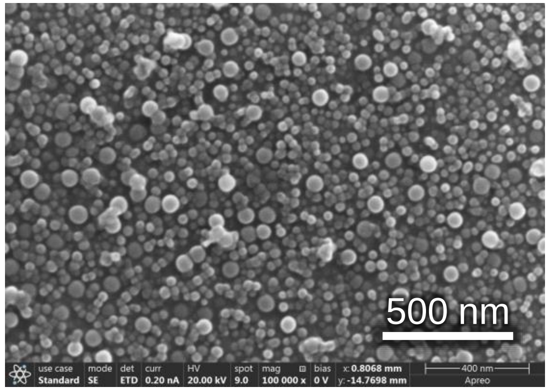
4h



6h

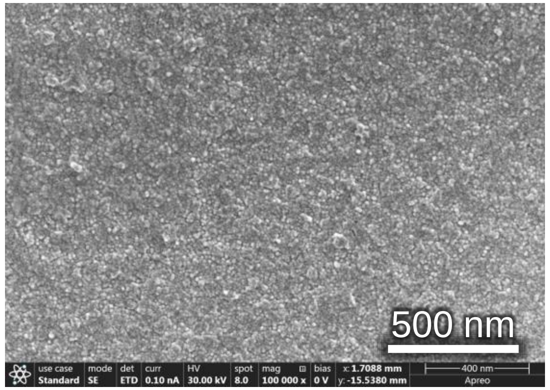


8h

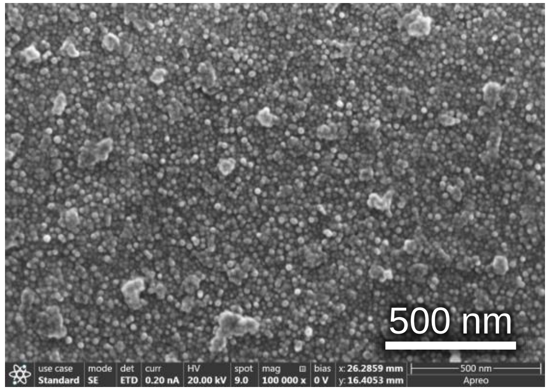


1150°C/2h + 1010°C/2h + 788°C/*x*h

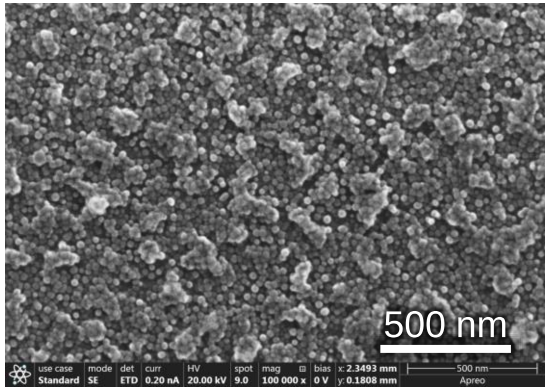
2h



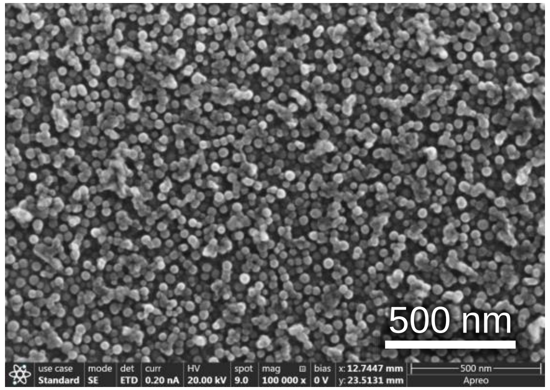
4h



6h



8h



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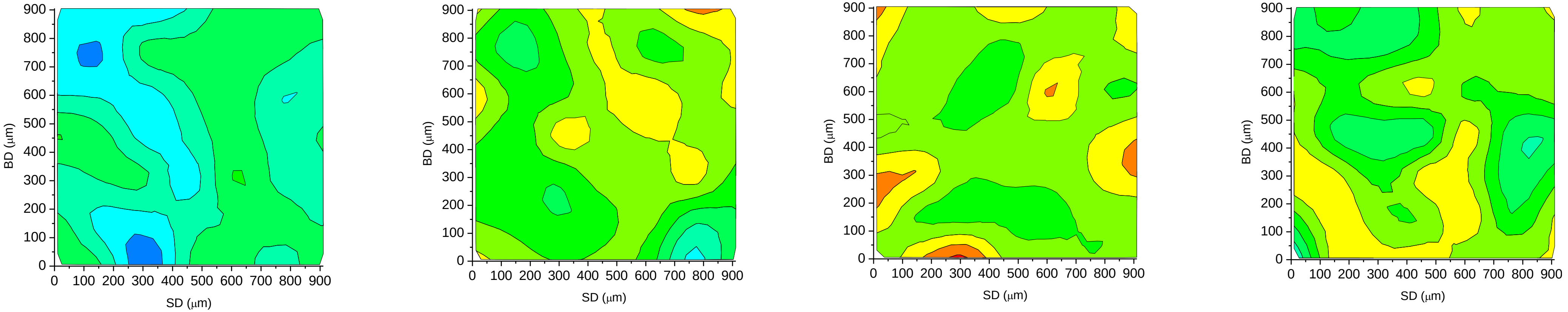
2nd Aging – hardness due to γ’ precipitation

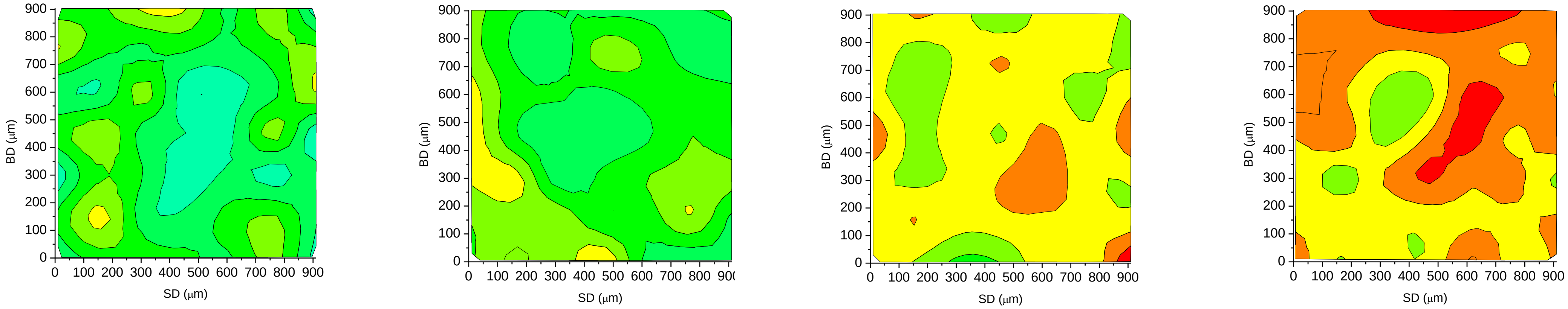
1250°C/2h + 1010°C/2h + 788°C/*x*h

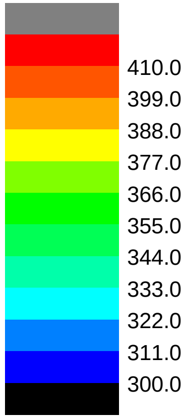
2h 4h 6h 8h



1150°C/2h + 1010°C/2h + 788°C/*x*h

2h 4h 6h 8h





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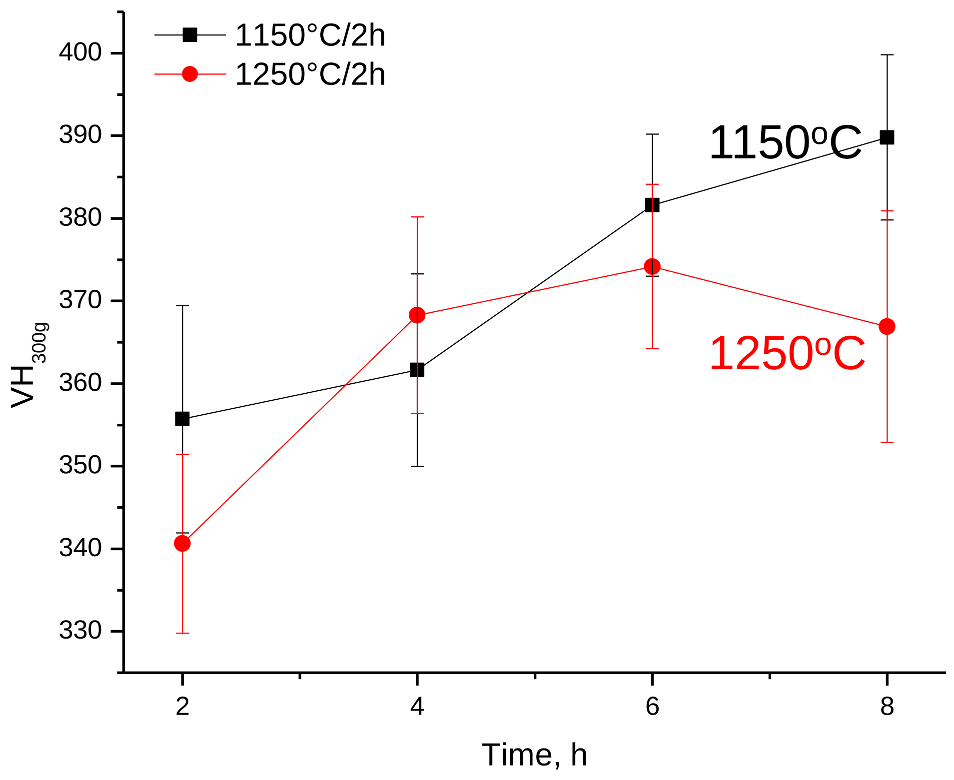
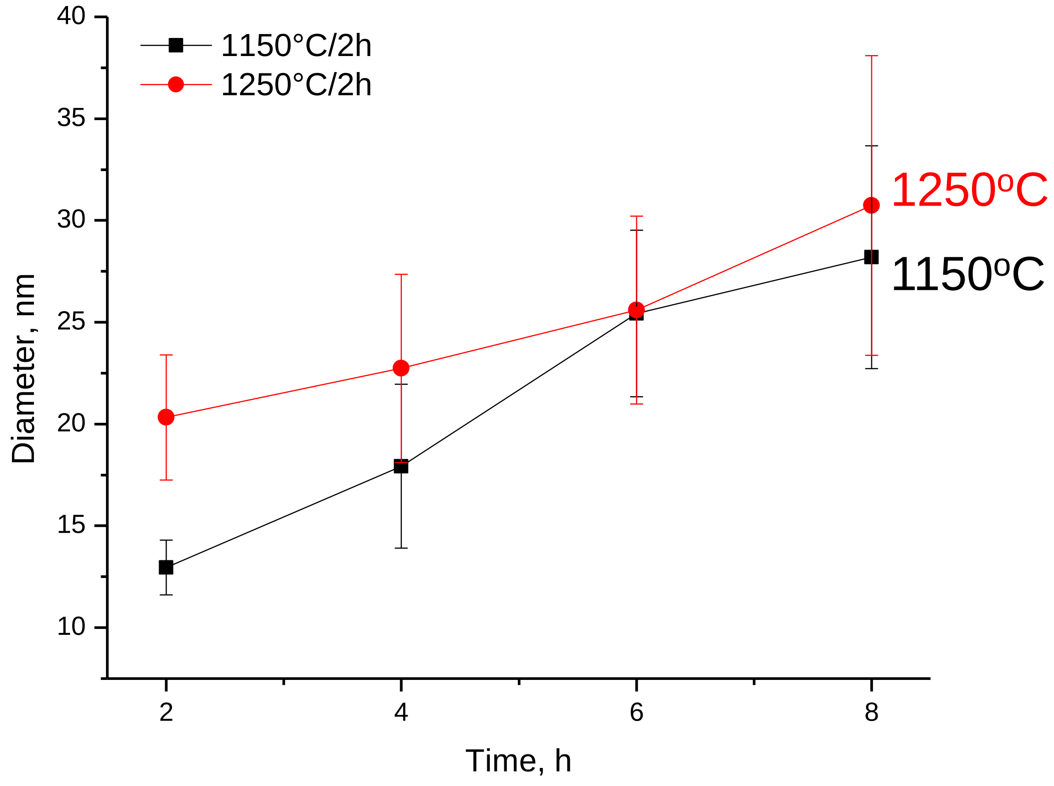
2nd Aging – hardness due to γ’ precipitation

Comparison of Hardness



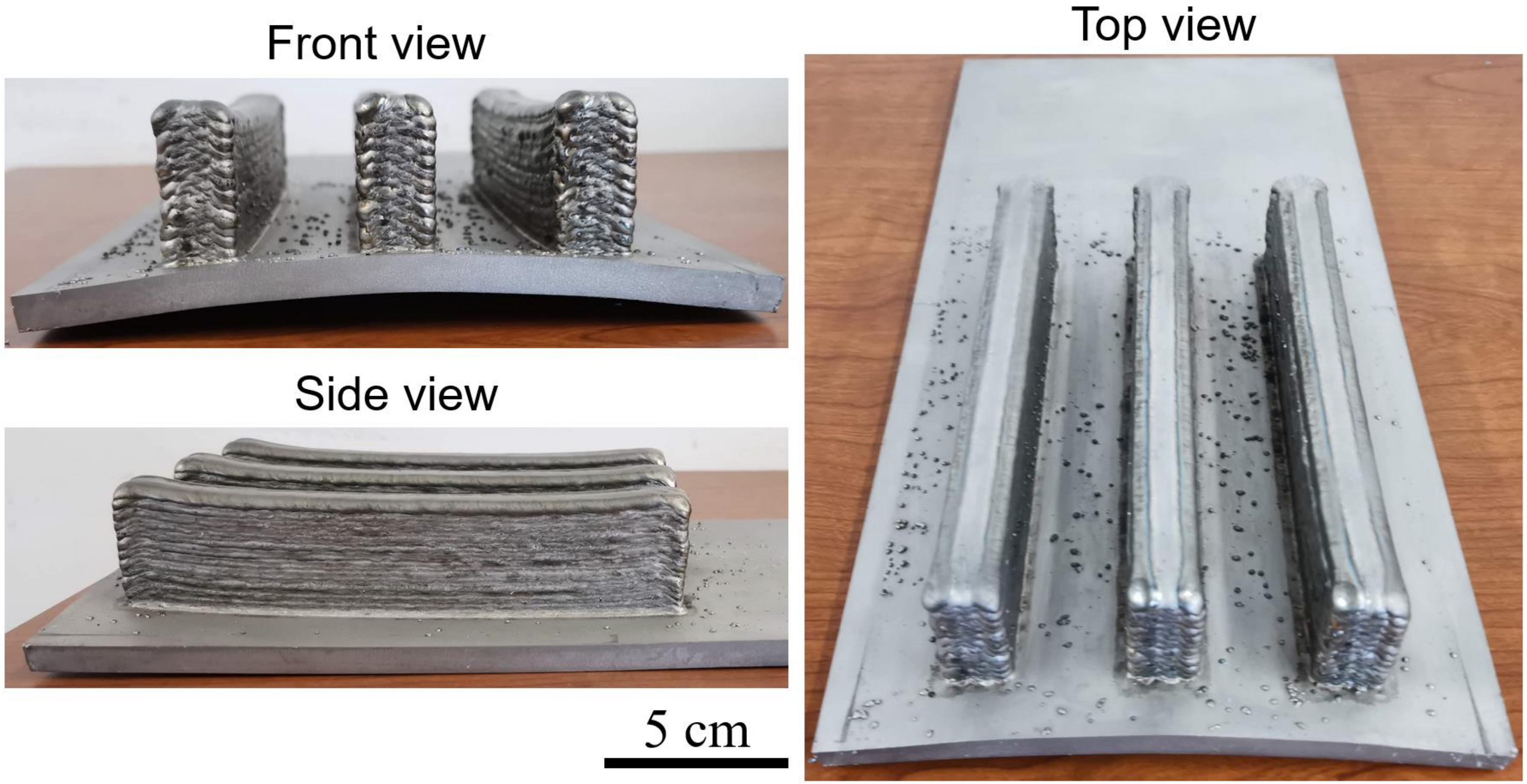
Comparison of average size of γ’ precipitation



Outline

- Background
- Recrystallization studies
- Grain structure modeling
- γ’ precipitation behavior
- Builds for high-throughput experiments
- Future work

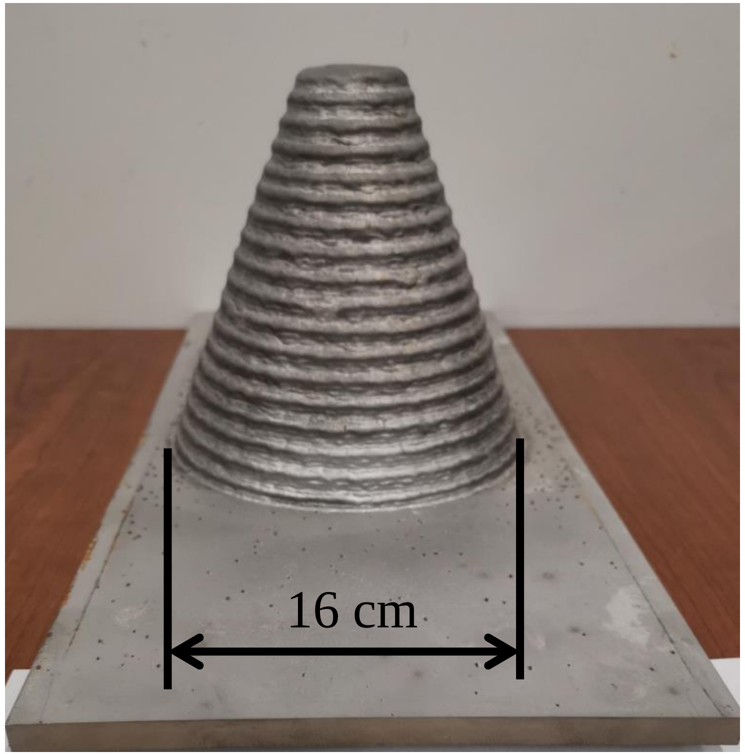
WAAM builds for high-throughput experiments



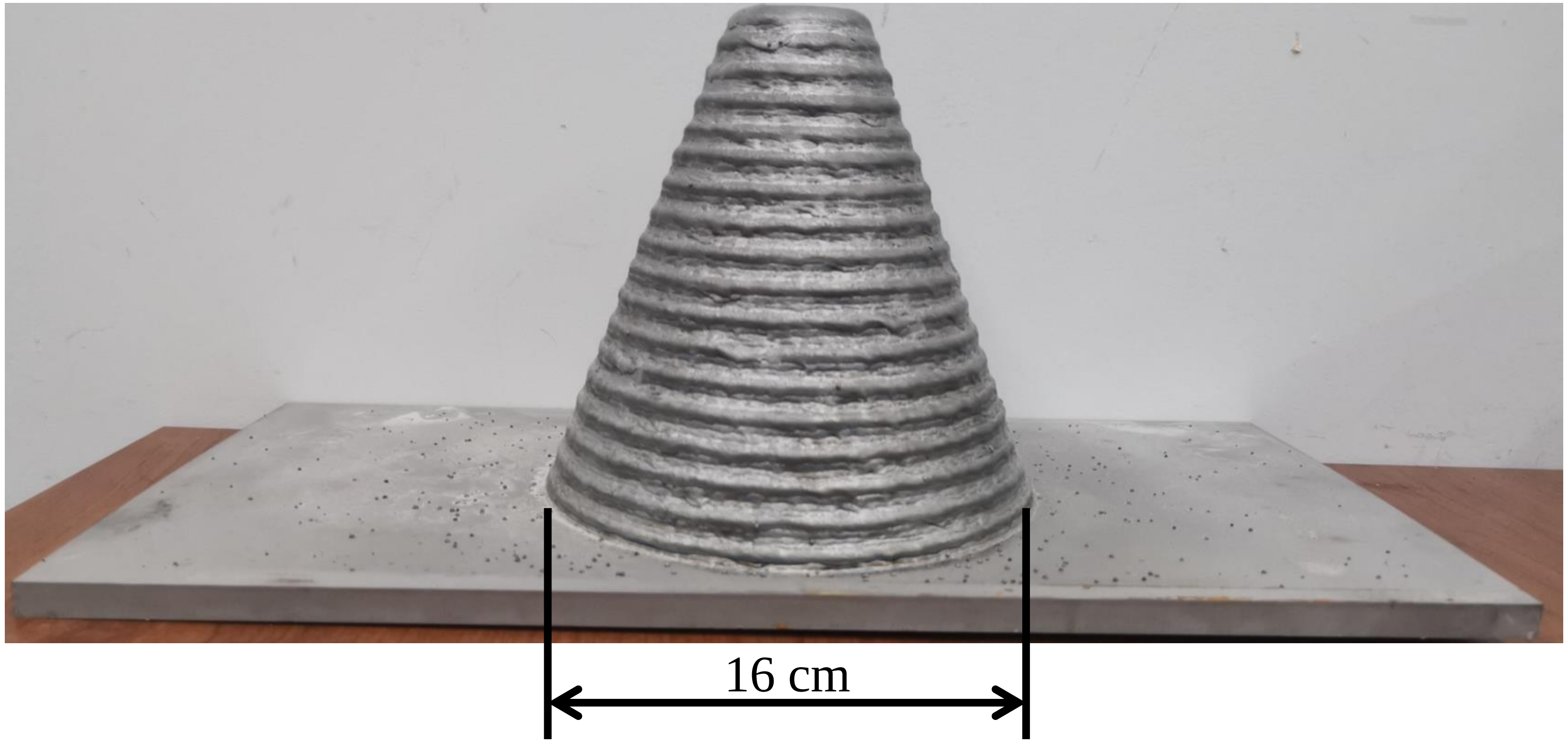
- Heavy distortion was observed at one end of the base plate while negligible distortion on the other end for the wall builds
- Distortion in the front end also varies along the longitudinal direction where the wall build at the middle is expected to possess a much higher distortion in comparison with the other two.

WAAM builds for high-throughput experiments

Side view

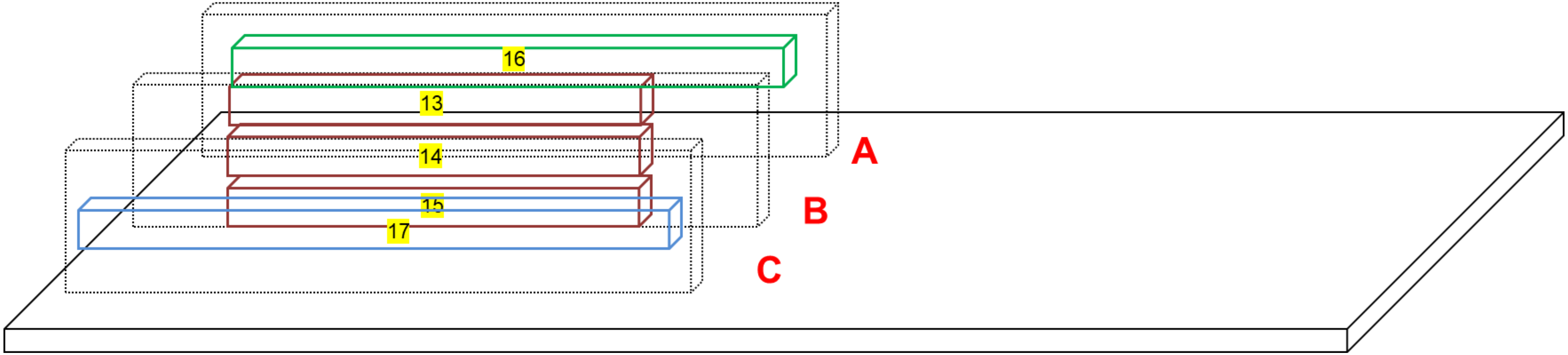


Front view



Cone build showed heavy distortion in the middle in comparison with the circumference

High-throughput experiment (ongoing)



Horizontal bars for high-throughput experiments

Gradient temperature furnace heat treatment

- Bars in B (3 bars): (13,14,15) Study of Aging time in the graded furnace with varying temperature at different times

Uniform temperature heat treatment

- Bar in A (1 bar): (16) Applying the traditional heat treatment to show the heterogeneity
- Bar in C (1 bar): (17) Applying the optimized heat treatment to show the homogeneity

Databank collection for location specific microstructural analysis

Location	Printing Parameters		Composition Variation [wt.%]	Experimental Variables		Modeling Variables	
Height (Z): Top | Middle | Bottom **Radius (±R) :** Left | Center | Right	Printing Pattern Layer Thickness Interlayer temperature Interlayer Idle time	Voltage/Current Pulse Power Wire Feed Rate Torch Traveling Speed & Working Distance Shielding Gas	Ni, Co Ti, Al Nb, Cr, Mo C, B Fe, Mn, Si	Phase fraction & composition Precipitate size Grain Size & morphology Dislocation Density Residual Stresses Texture	Vickers Hardness	Phase fraction & composition Precipitate size Liquidus Solidus Freezing Rage TEC, α Latent heat, L	Yield Strength Vickers Hardness

Input for ICME/ML models

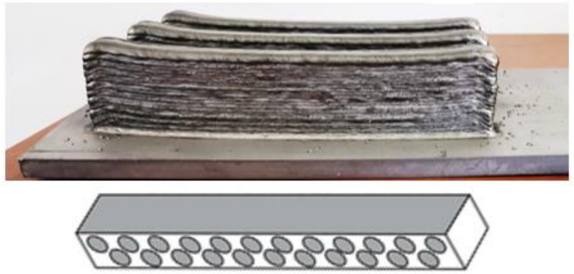
Planned studies in this project

Identify an approach to introduce more uniform structure-property correlations in large prints.

Can we identify a good approach to post-heat treat the sample minimizing anisotropic structure-property relationship?

Yes

Can we apply this to other types of geometry?

A	B
	 Cone shape
HT WAAM sample with gradient temperature and processing parameter	Complex geometry build for location specific ICME design

Dissemination

Published research paper

- H. Zhang, Y. Wang, R. Rodriguez De Vecchis, W. Xiong, "Evolution of carbide precipitates in Haynes® 282 superalloy processed by wire arc additive manufacturing", Journal of Materials Processing Technology, 305 (2022) 117597, https://doi.org/10.1016/j.jmatprotec.2022.117597

Manuscript under development

- L. Pizano, P. Santanu, S. Sridar, Y. Wang, C. Sudbrack, A. To, W. Xiong, “Microstructure engineering of Haynes 282 alloys prepared by wire arc additive manufacturing using post-heat treatment”, (2022)

Conference presentations and invited seminars

- “Wire-Arc Additive Manufacturing of Alloy Components from Traditional Alloys to Functionally Graded Materials”, International Conference on Additive Manufacturing, JW Marriott - Anaheim, CA, USA, Nov 1-5, 2021.
- “ICME Gap Analysis for Materials Design and Process Optimization in Additive Manufacturing”, Symposium: Additive Manufacturing of Metals: ICME Gaps: Material Property and Validation Data to Support Certification, MS&T 2021, Columbus, Ohio, USA, Oct 17-21, 2021.
- “Materials Genome, ICME, and Additive Manufacturing”, AM Seminar Series, Virtual, National Institute of Standard and Technology, Jan. 20, 2022
- “High-throughput Computation and Experiments for Materials Design in Additive Manufacturing”, Invited presentation for annual meeting, Virtual, CHiMaD center, Northwestern University, Oct. 5, 2021.

Acknowledgment: "This material is based upon work supported by the Department of Energy Award Number UCFER RFP 2020-06 / DE-FE0026825."

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