



Effect of Heat Treatment on Microstructure and Mechanical Property of 316L Stainless Steel Produced by Laser Powder Bed Fusion

June 2024

Changing the World's Energy Future

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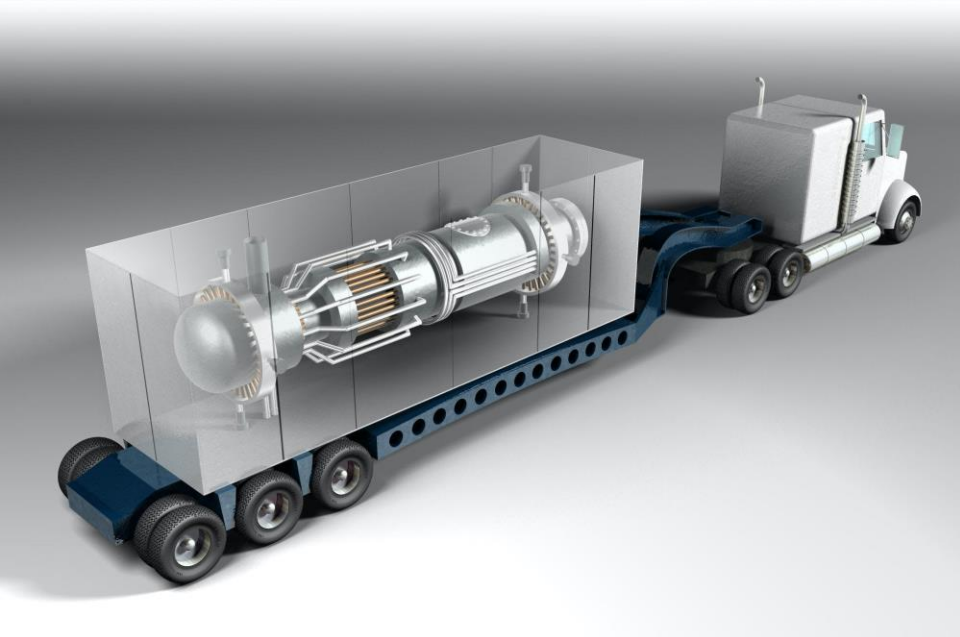
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June 2024

**Idaho National Laboratory
Idaho Falls, Idaho 83415**

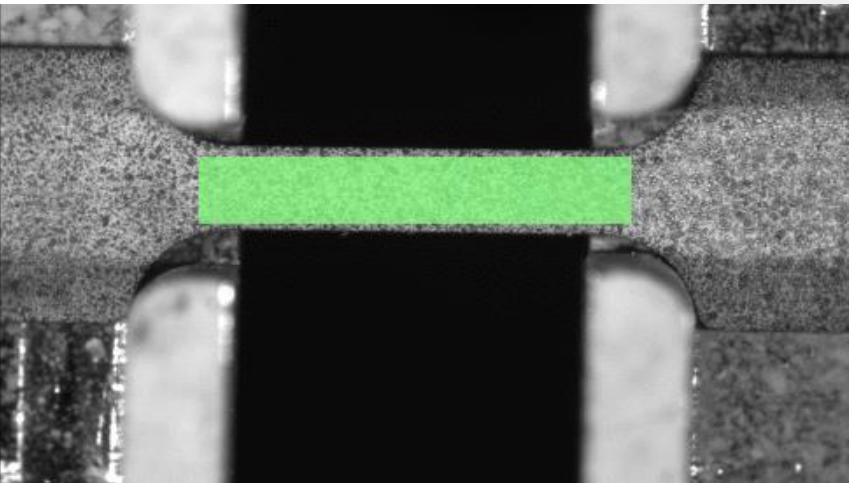
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2024 ANS Annual Conference

June 16–19, 2024

Las Vegas, NV | Mandalay Bay Resort and Casino

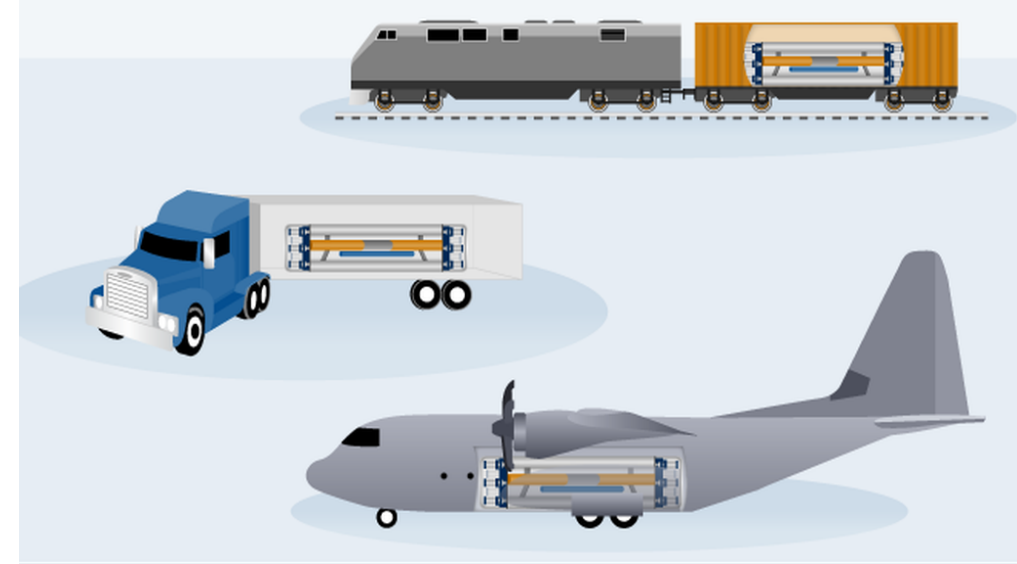
Battelle Energy Alliance manages INL for the
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Idaho National Laboratory

Fission Batteries Concept

- **Fission batteries (FBs) are “plug-and-play” microreactors**
 - Mobile power source
 - Provide heat demands, replacing oil and natural gas in a low-carbon economy
 - Individual FB would have outputs between 5 and 30 MWt
- **Self-contained, off-grid, expandable, factory-made**
 - Shipped whole from factory and returned whole to factory after use
 - Refurbishment, fuel cycle and waste management operations done at factory
- **Enables rapid deployment of power to remote areas or areas after catastrophic damage with minimal infrastructure requirements**



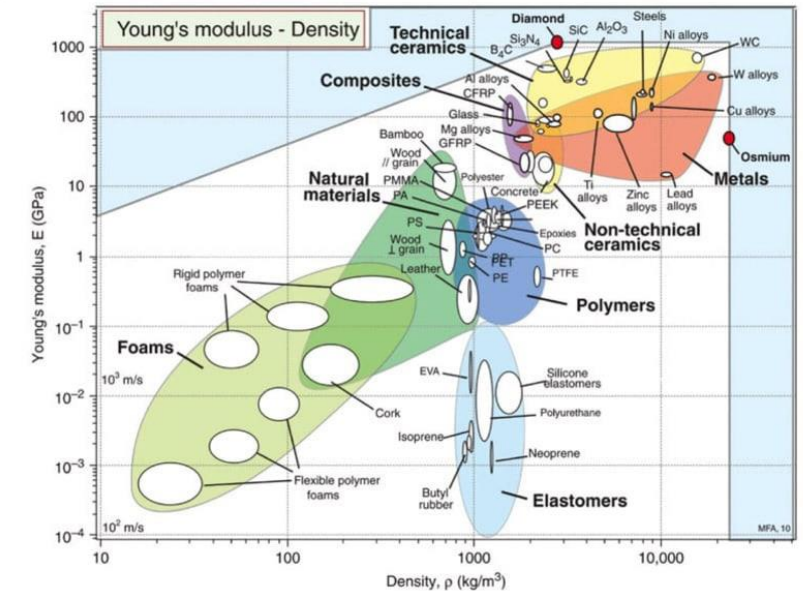
A powertrain of a mobile vehicle



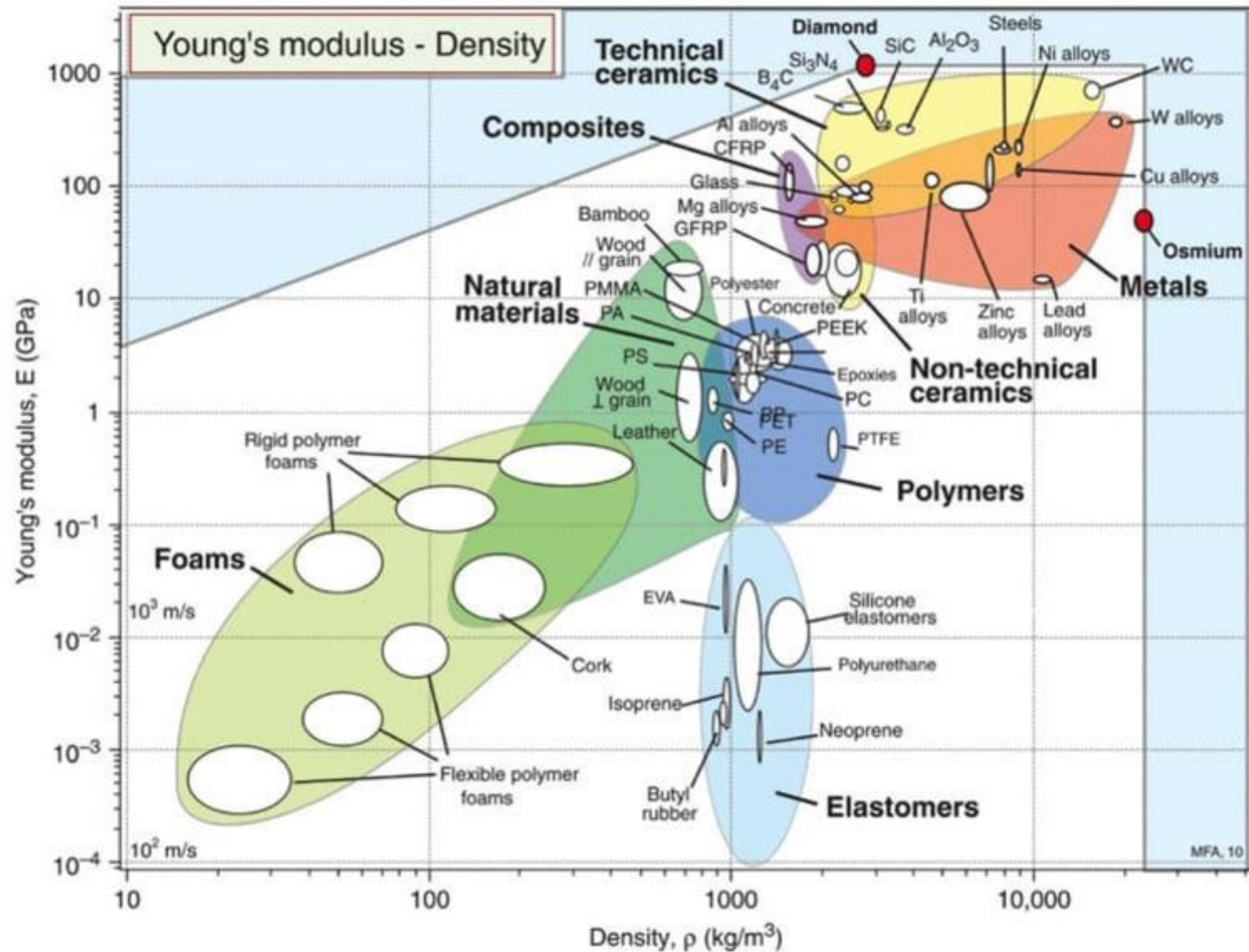
X-energy Xe-Mobile

Structural Materials Requirements for Fission Batteries

- **Lightweight**
 - Ease of transport
- **Structural resilience**
 - Under various operational, repeated shutdown, transportation, startup cycles, and external conditions
 - Feature a good combination of mechanical properties
- **Approaches of Lightweight**
 - Low density materials selection

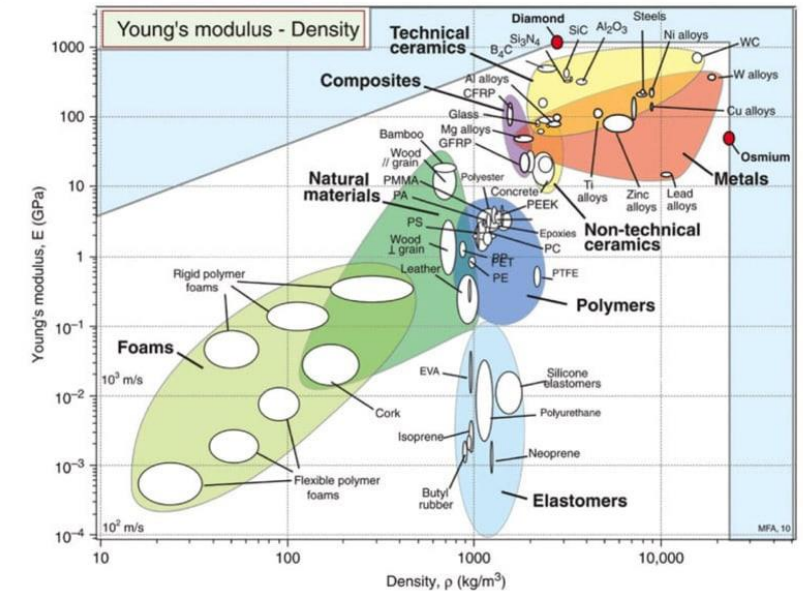


Ashby Chart for evaluating stiffness-to-weight ratio of conventional materials.

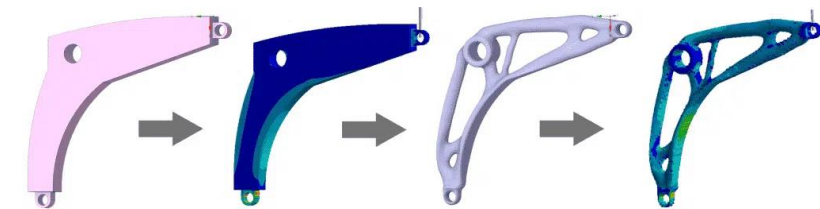


Materials Requirements for Fission Batteries

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- **Structural resilience**
 - Under various operational, repeated shutdown, transportation, startup cycles, and external conditions
 - Feature a good combination of mechanical properties
- **Approaches of Lightweight**
 - Low density materials selection
 - Topology optimization
 - Lattices and architected materials



Ashby Chart for evaluating stiffness-to-weight ratio of conventional materials.



Topology Optimization of a Bell Crank

Additive Manufacturing of Lightweight Materials

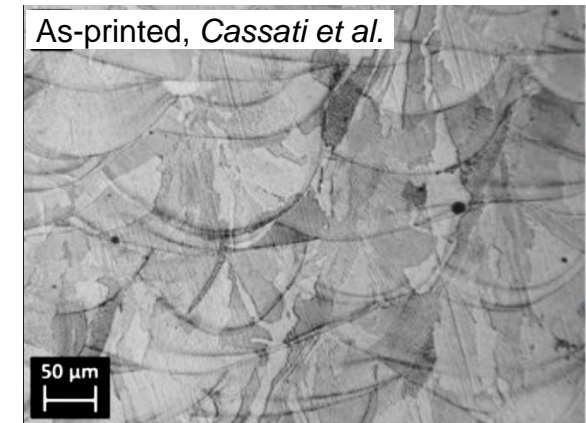
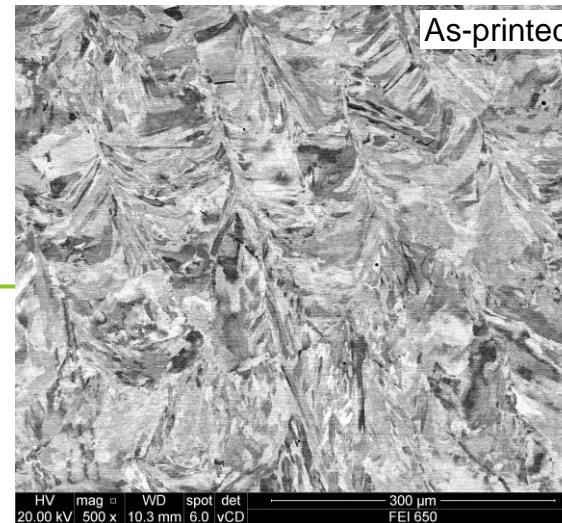
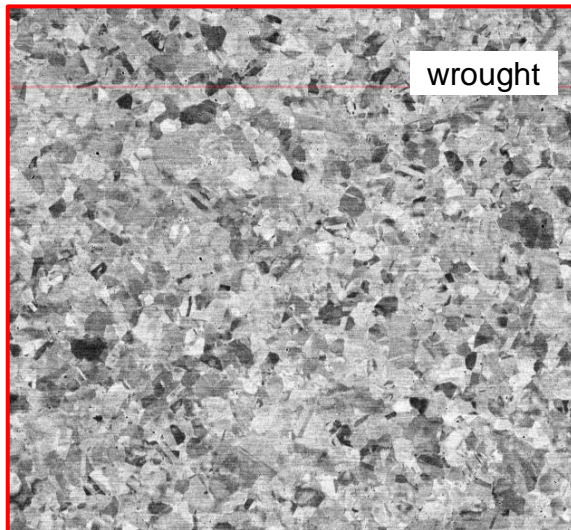
- **Additive manufacturing (AM)**
 - Enables material geometries not producible by traditional means
 - Offer superior properties with respect to irradiation void swelling resistance
- Due to the high-temperature, high-strength requirements of nuclear applications, lattice structured 316L stainless steels by AM was pursued rather than substitution with low density alloys (e.g., aluminum, magnesium, *et al.*)



Promotional photos of parts produced using an Open Additive PANDATM, LPBF printer available at the Center for Advanced Energy Studies (CAES) at Idaho National Laboratory

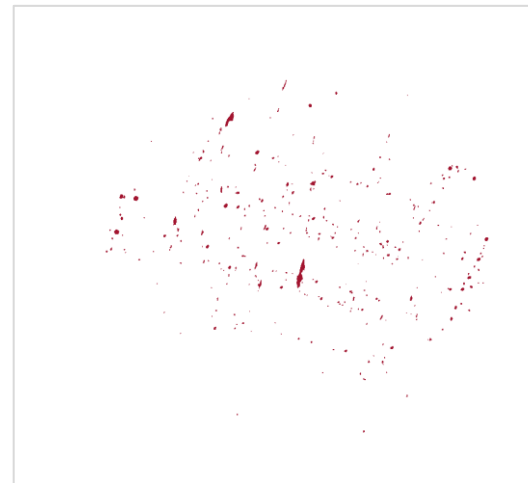
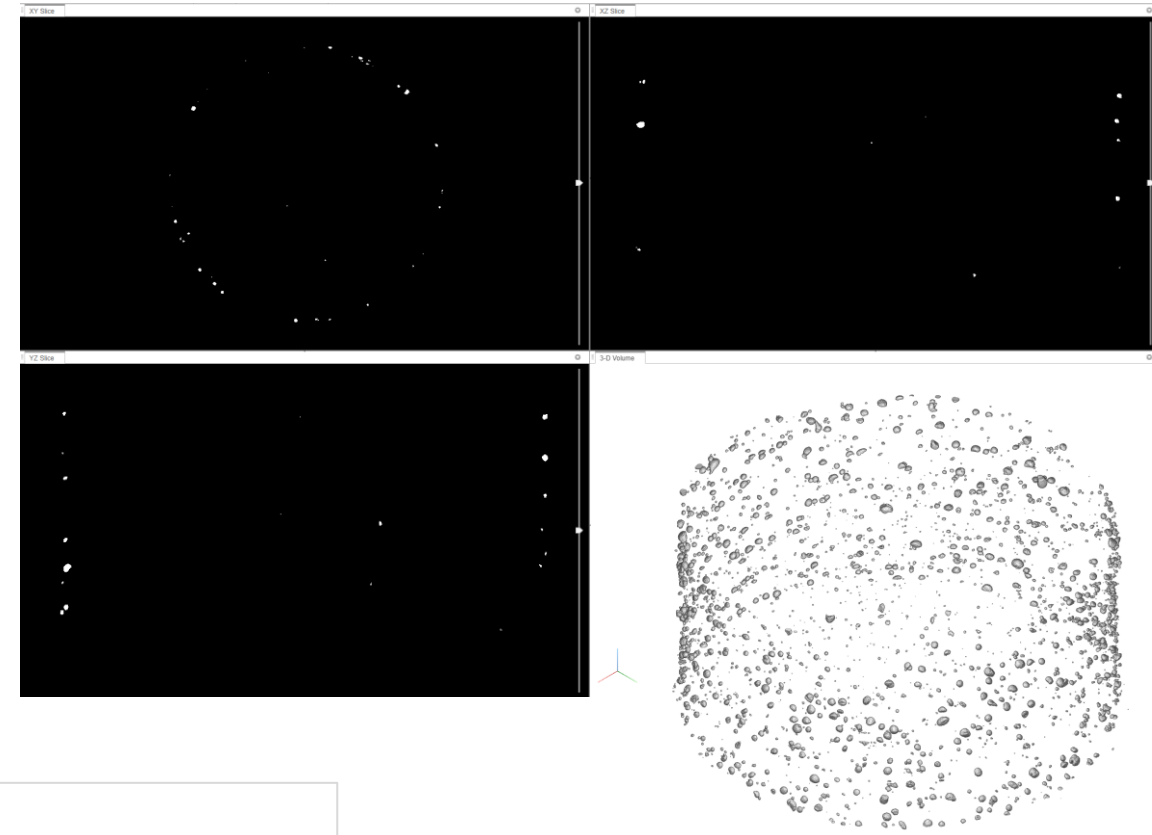
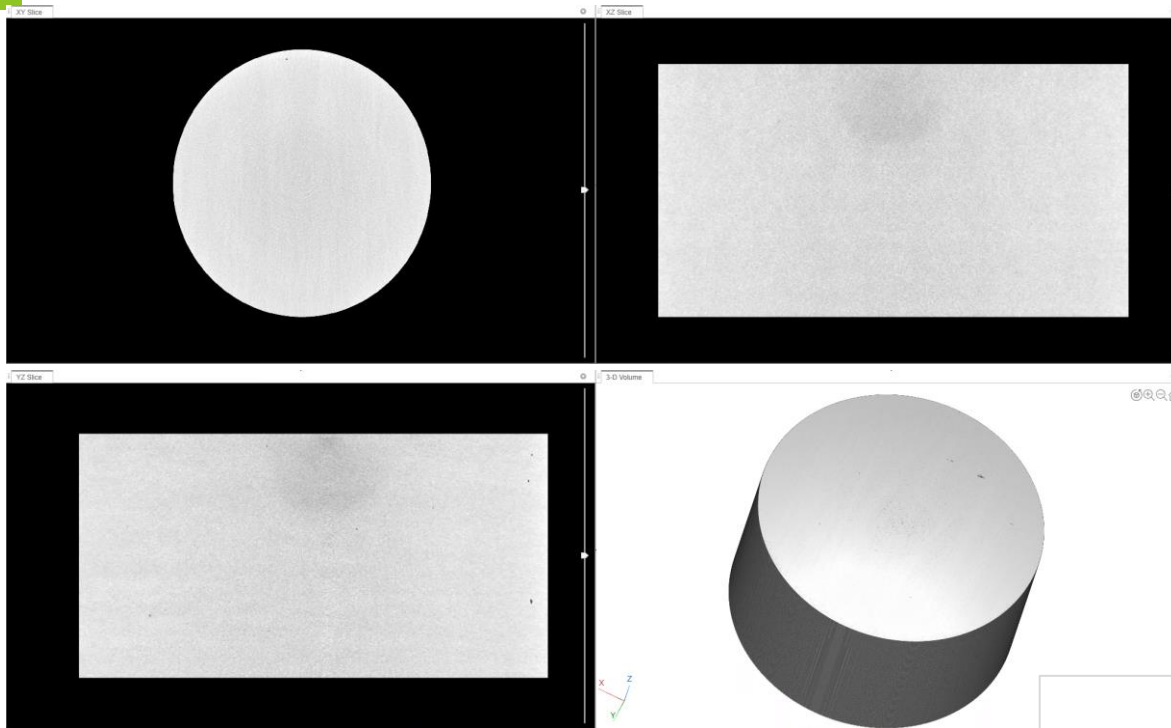
Necessity of Heat Treatment for AM Metal

- The rapid heating and cooling involved in AM process result in heterogeneous microstructures and the accumulation of internal stresses.
- Post-processing heat treatment is often needed to modify the microstructure and/or alleviate residual stresses to achieve desired properties.
- The heat treatment conditions need to be determined
- **Objective**
 - Determine the heat treatment conditions for the LPBF printed solid sample to have similar strength as the wrought material

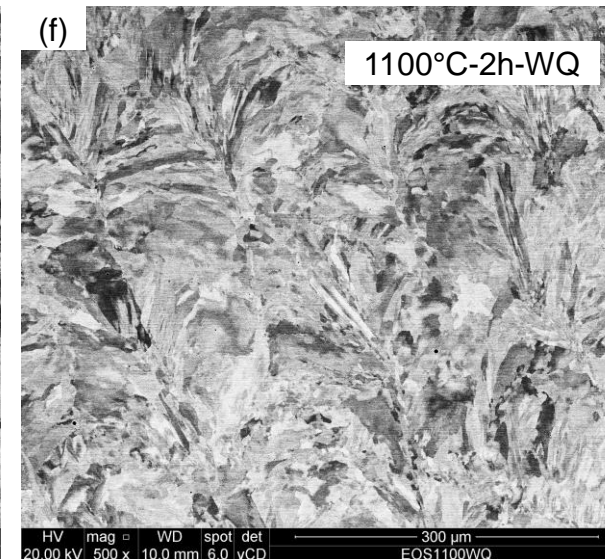
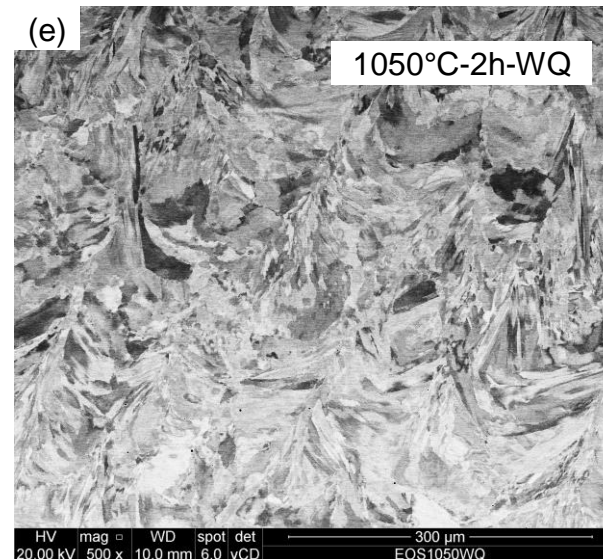
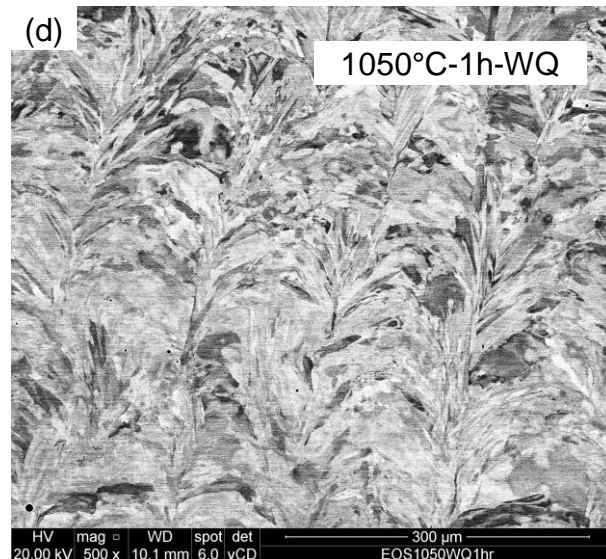
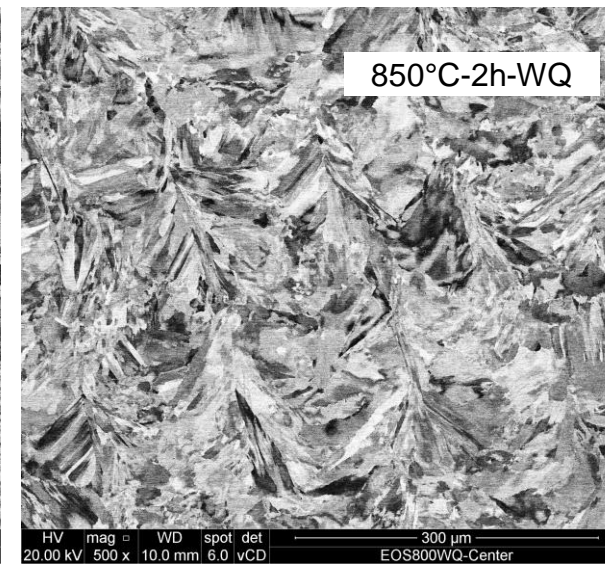
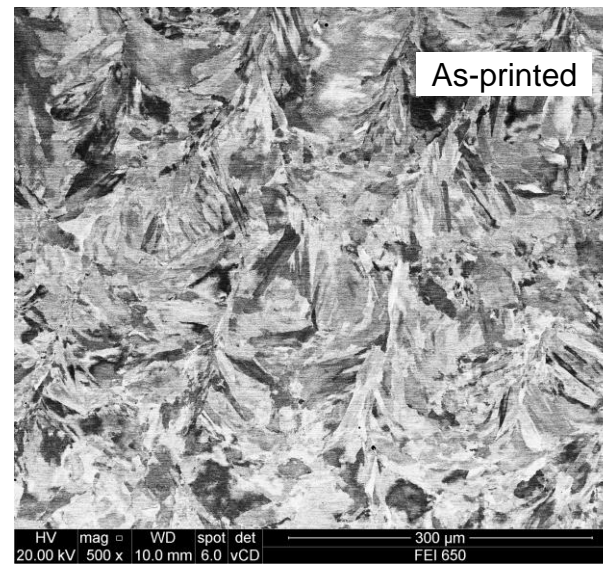
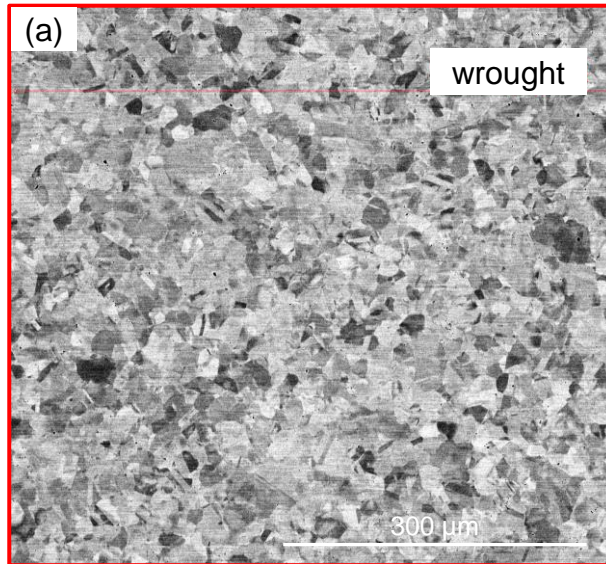


R. Cassati *et al.* *J. of Mater. Sci. & Technol.* 32(2016)738.

LPBF Printed Sample

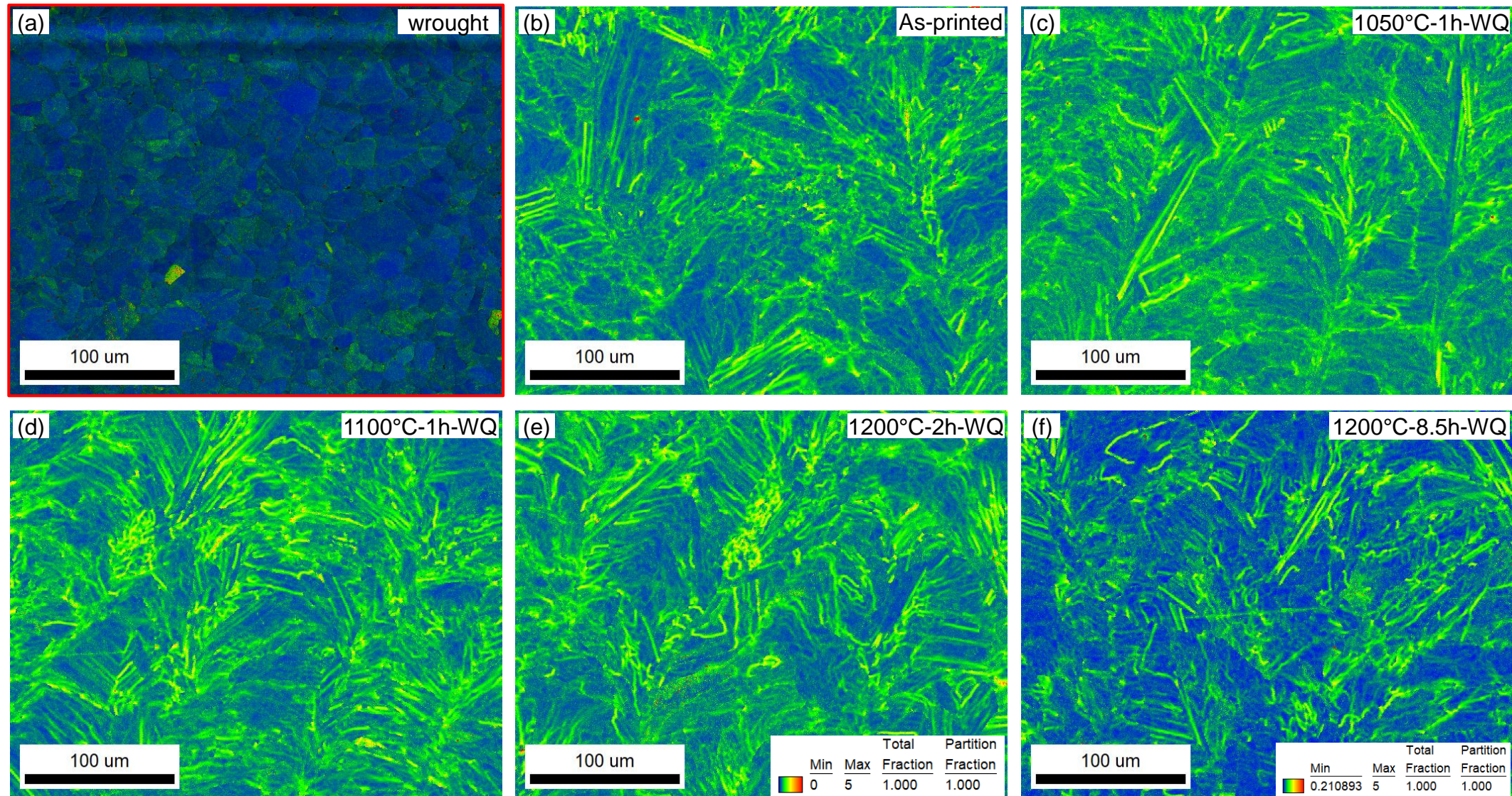


Effect of Heat Treatment on Microstructure

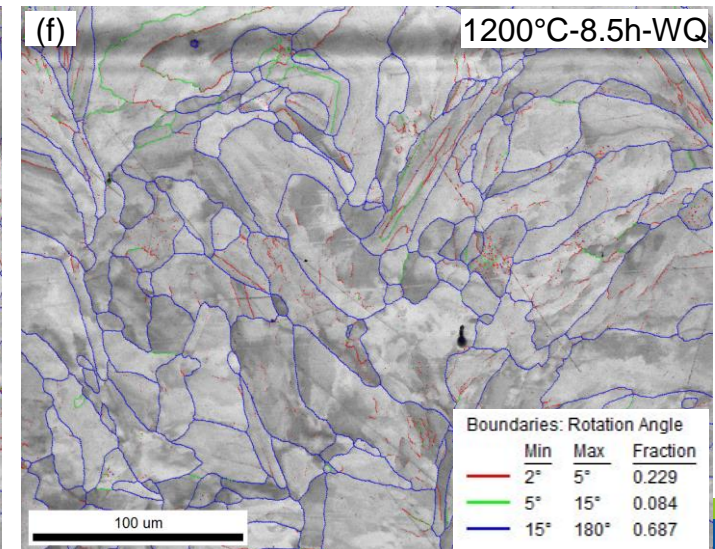
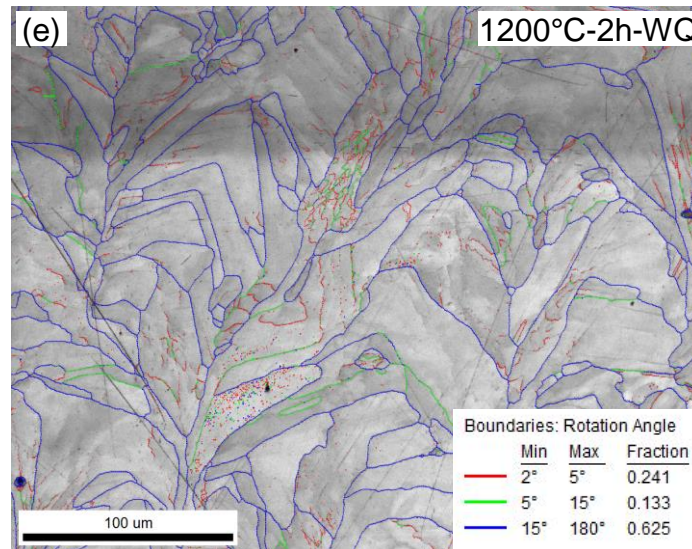
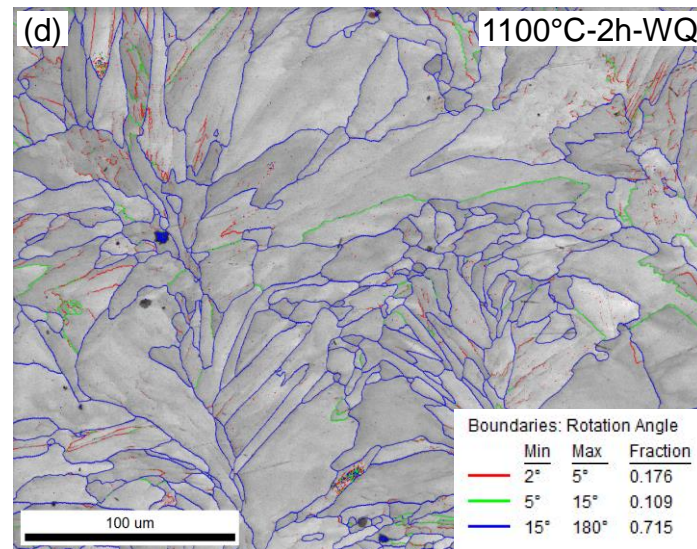
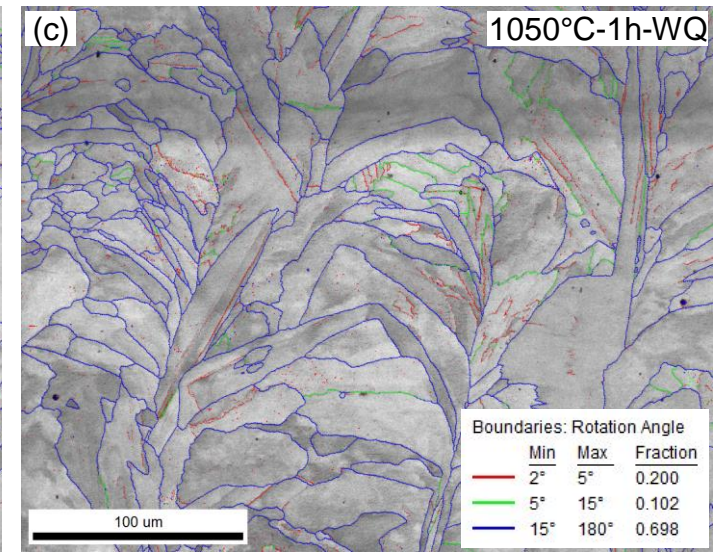
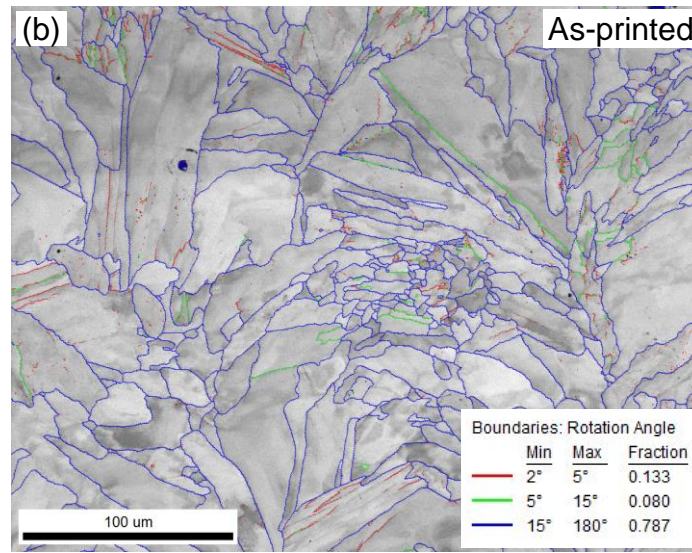
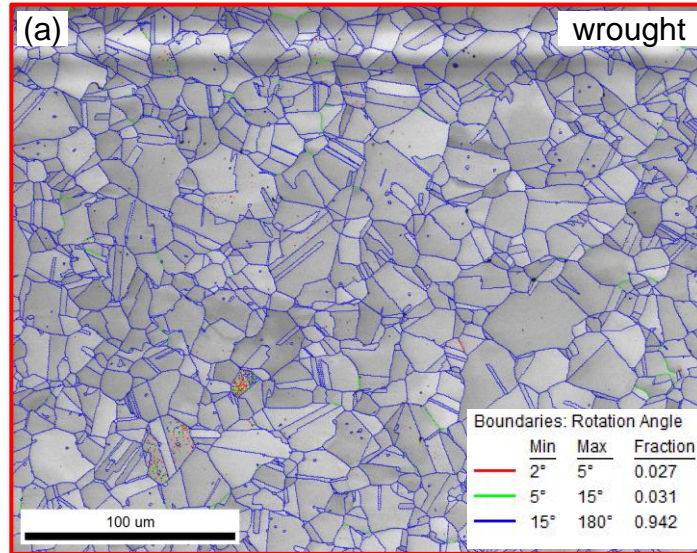


LPBF printed SS
316L, 800 °C to
1200 °C in 50 °C
increments for 1-24
hours, followed by
water quenching

Kernel Average Misorientation

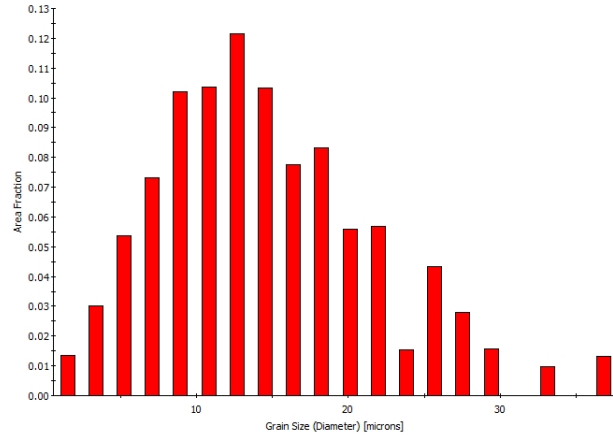


Grain Boundary Misorientation

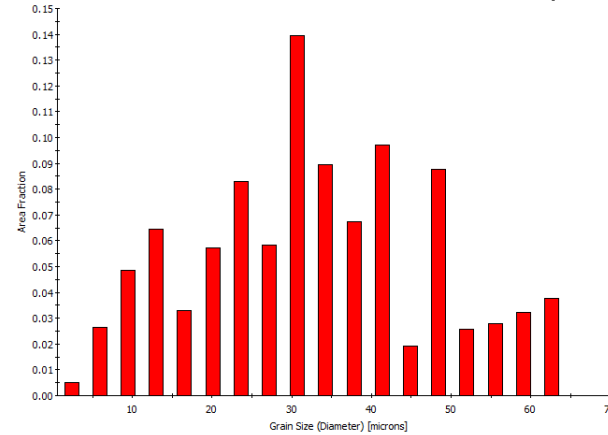


Grain Size

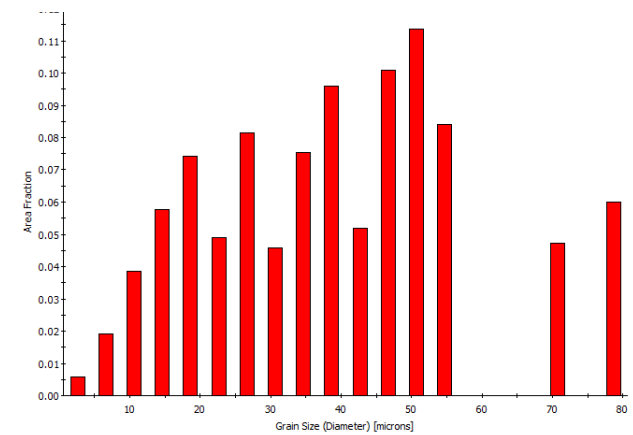
(a) Grain size: 14.7 ± 7.1 wrought



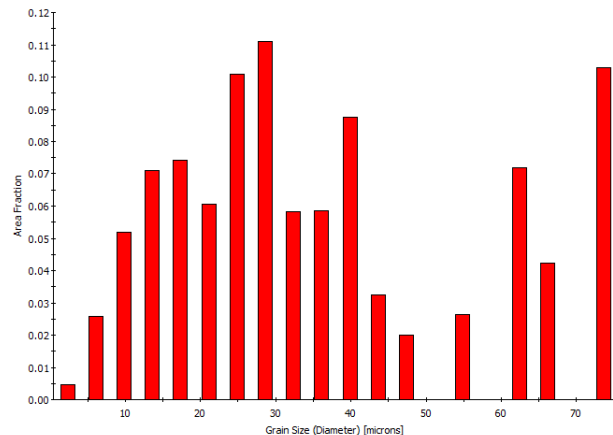
(b) Grain size: 32.5 ± 14.5 As-printed



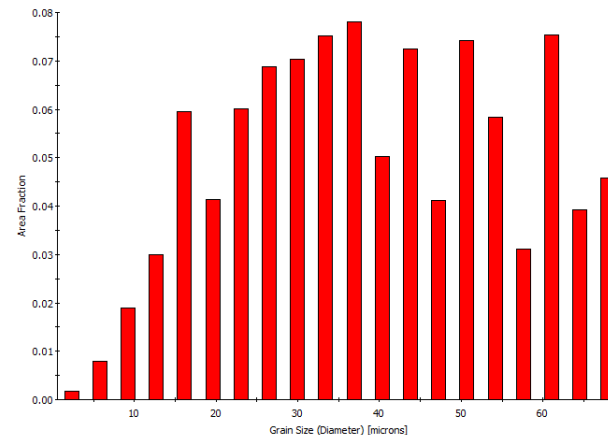
(c) Grain size: 39.3 ± 18.8 1050°C-1h-WQ



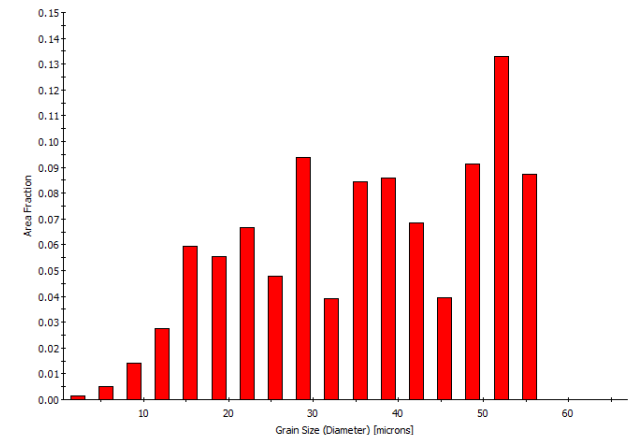
(d) Grain size: 36.1 ± 20.6 100°C-2h-WQ



(e) Grain size: 39.4 ± 16.7 200°C-2h-WQ

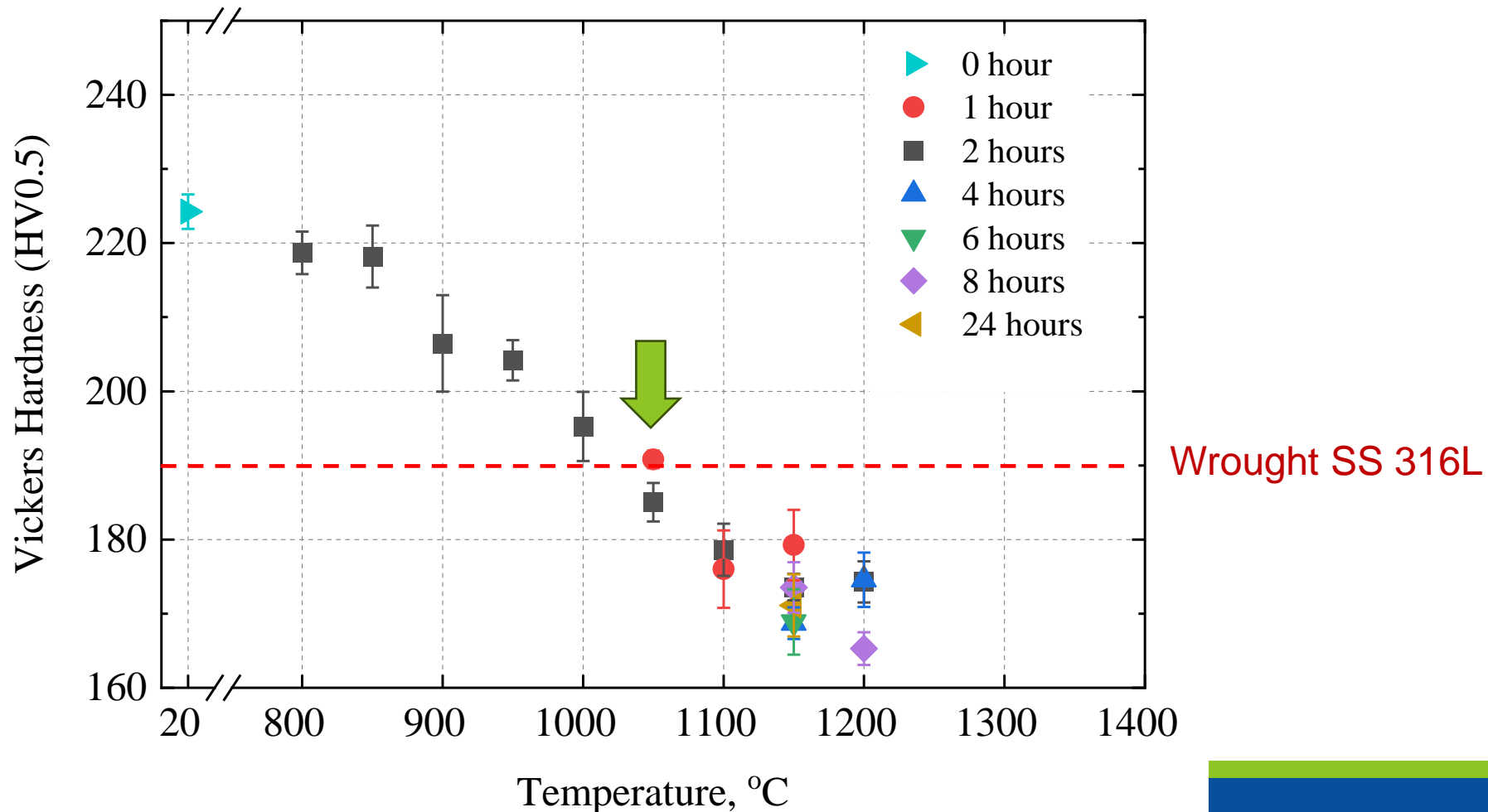


(f) Grain size: 36.4 ± 13.8 1200°C-8.5h-WQ

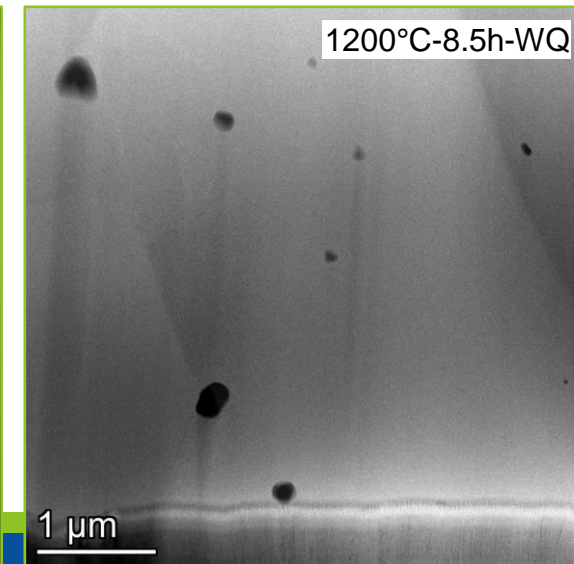
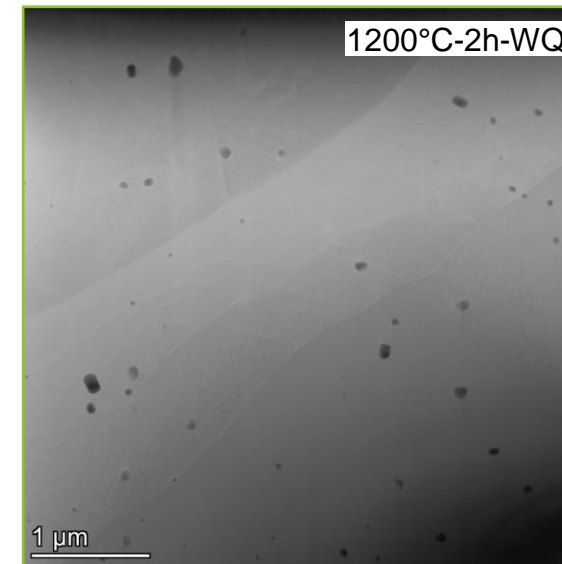
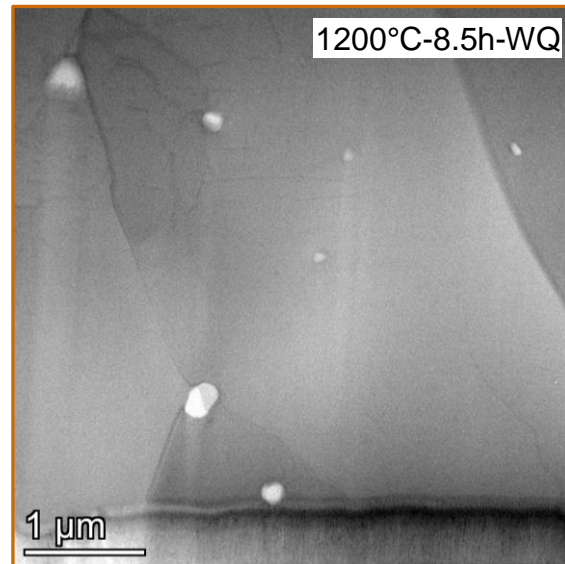
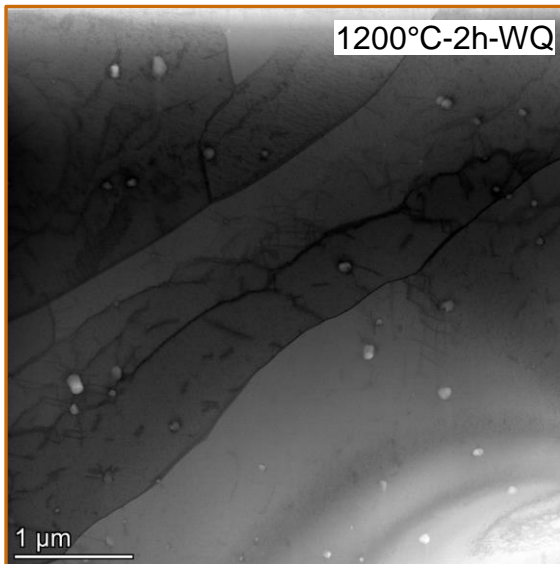
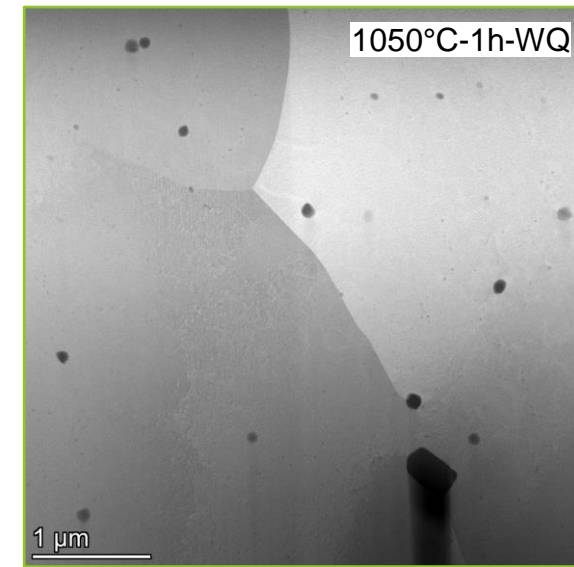
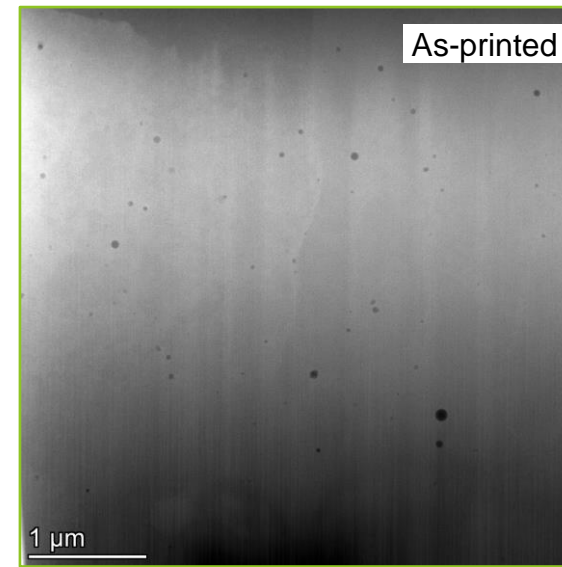
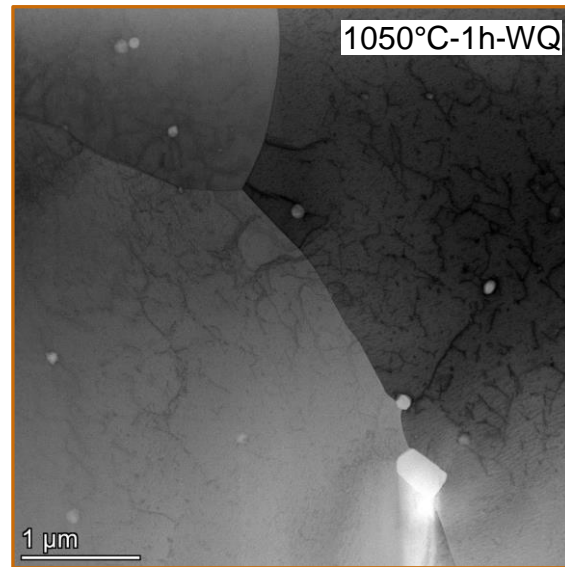
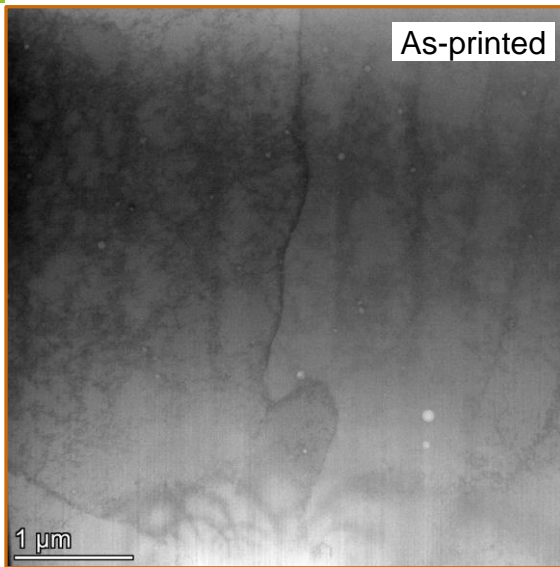


Effect of Heat Treatment on Hardness

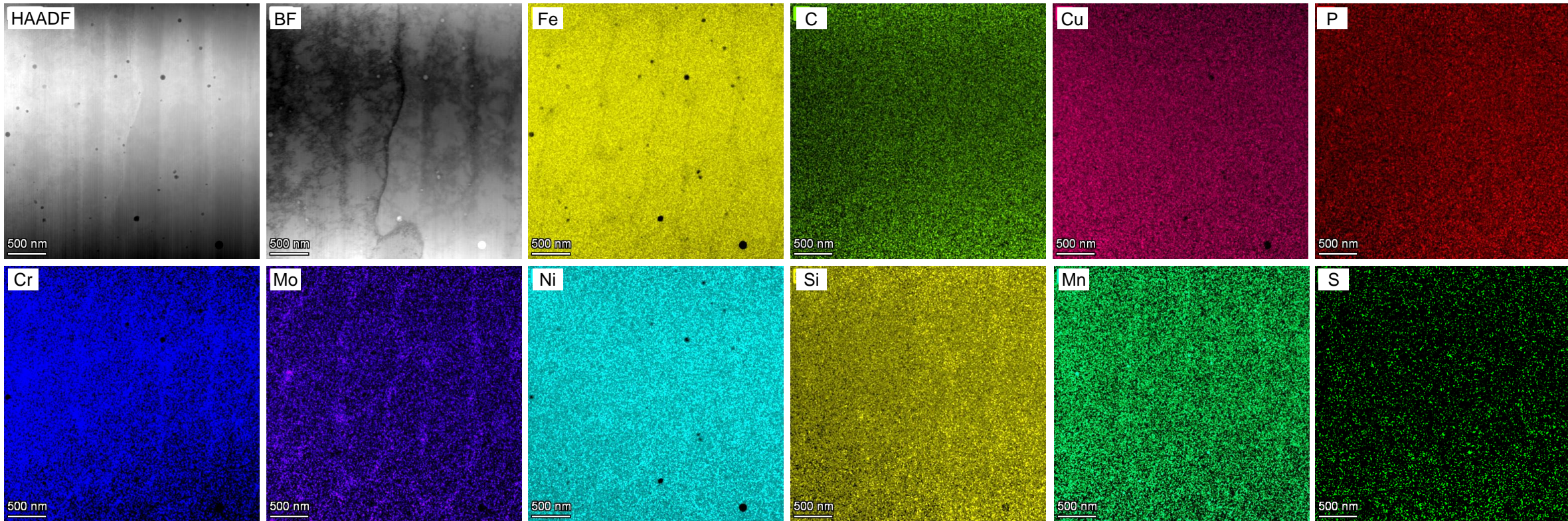
- LPBF printed SS 316L, 800 °C to 1200 °C in 50 °C increments for 1-24 hours, followed by water quenching



TEM Bright Field and High-Angle Annular Dark-Field

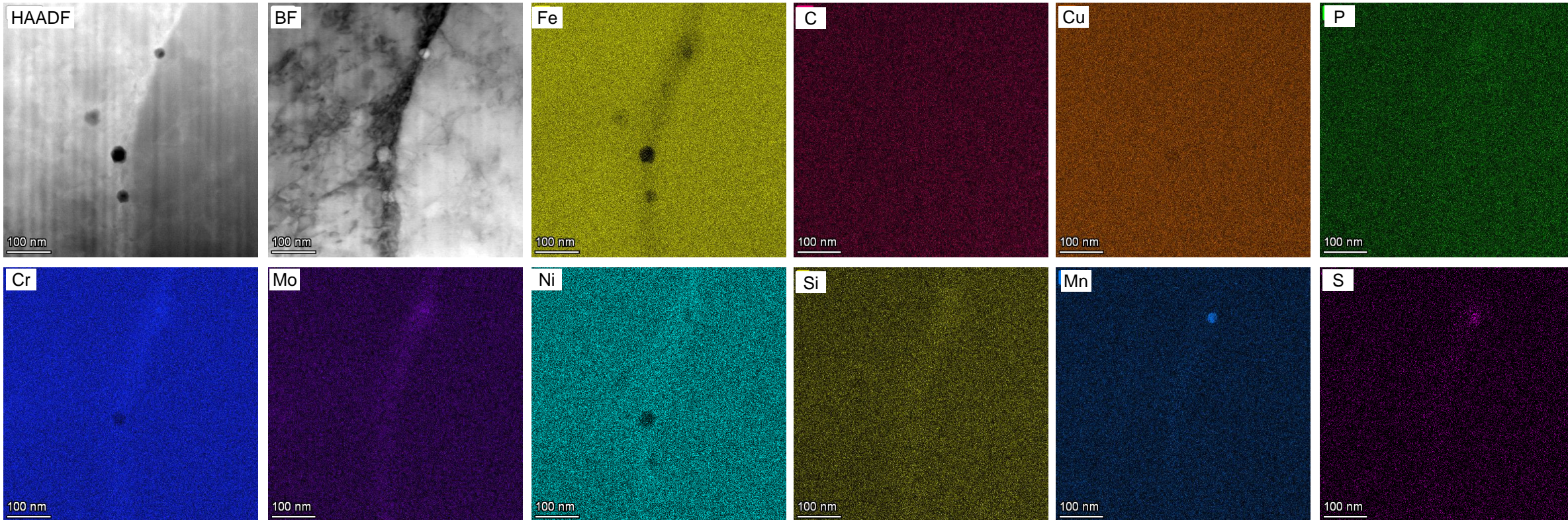


EDS Analysis — As Printed



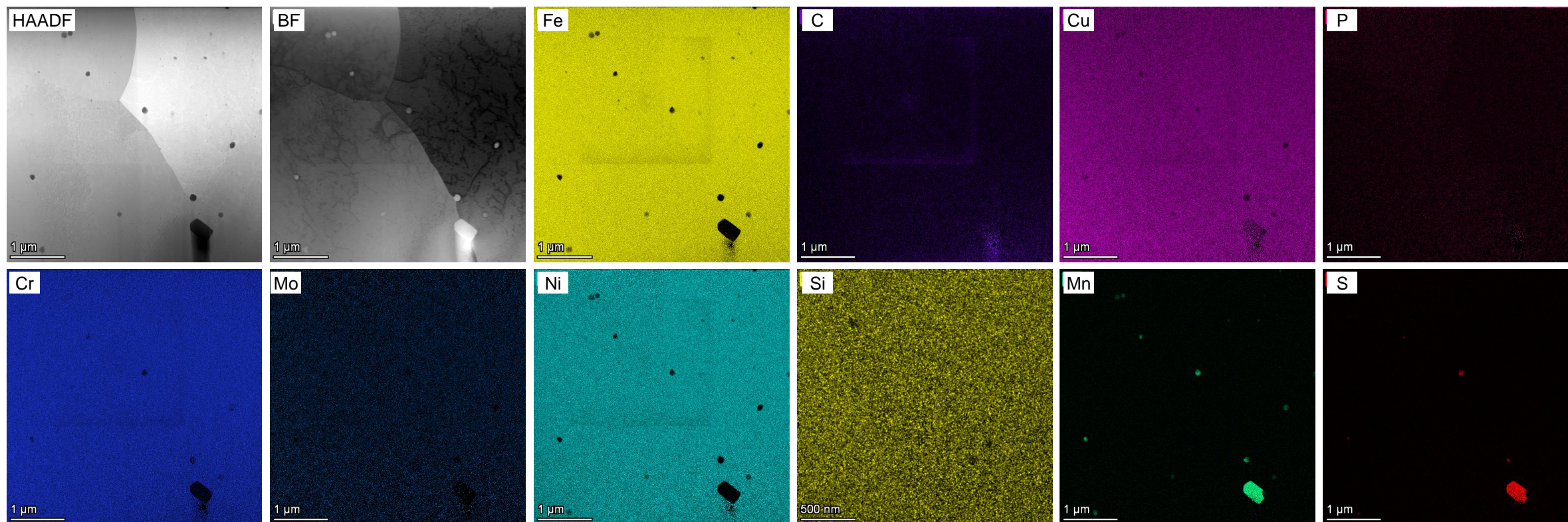
Cr, Mo, Ni, Si enrichment on the sub-grain boundaries.

EDS Analysis — As Printed



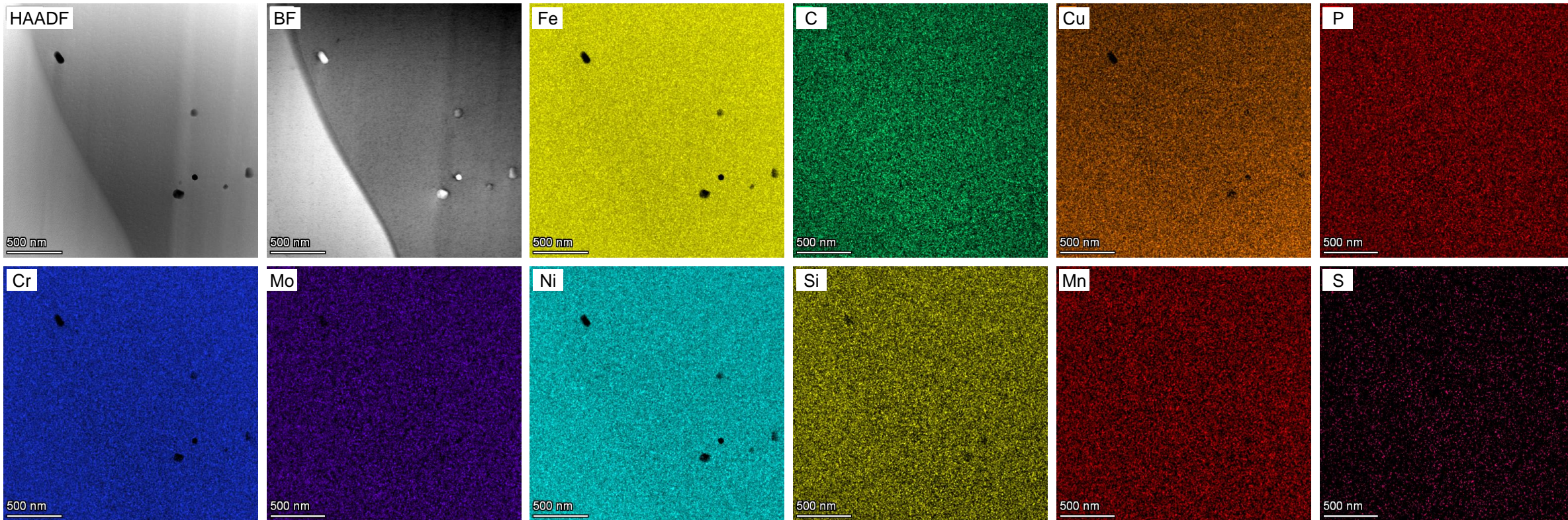
Cr, Mo, Ni, Si enrichment on grain boundary. MnS inclusion on grain boundary.

EDS Analysis — 1050°C-1h-WQ



The alloying element enrichment at grain boundary disappeared after solution anneal.
MnS inclusion on grain boundary.

EDS Analysis — 1200°C-8.5h-WQ



The alloying element enrichment at grain boundary disappeared after solution anneal.

Summary

- Fission batteries and approaches of lightweighting are introduced.
- The LPBF process produces a solidification structure with lots of dislocation substructure.
- Annealing at temperatures up to 1200 °C does not produce fully recrystallization or significant grain growth but does produce recovery of the dislocation (sub)structure.
- Cr, Mo, Ni, Si shows enrichment on the (sub)grain boundary in the as-printed sample, but not in the SA sample.
- The increase in heat treatment temperature decreases hardness.
- 1050 °C for 1 hour and air cool was selected for heat treatment of LPBF printed samples to match a similar hardness level as wrought material.

Acknowledgement

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Idaho National Laboratory

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