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Laser Additive Manufacturing of Fe-Si Based Soft Magnetic Alloys

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Sandia National Laboratories

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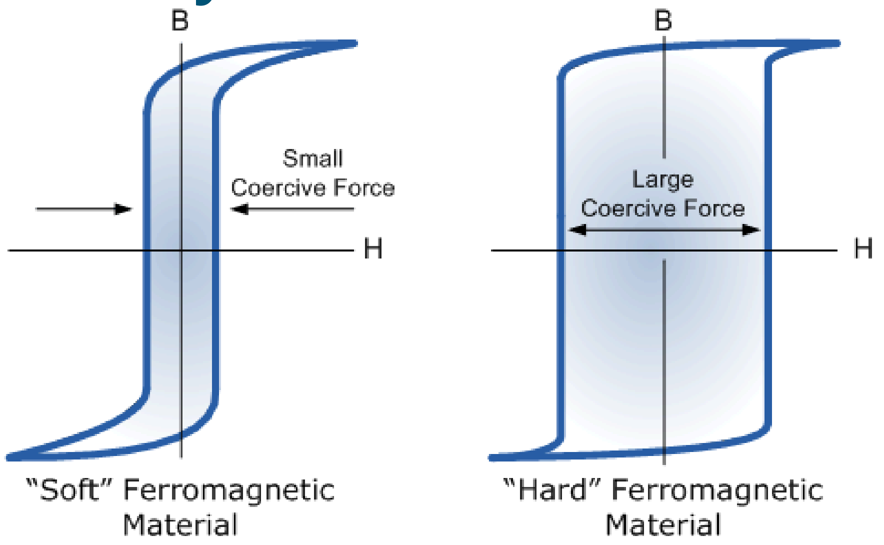
Fundamentals of soft magnetic alloys

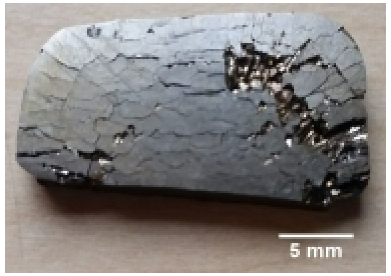
Excellent soft magnetic properties:
- High saturation induction
- High permeability (High *B* for low *H*)
- Low coercivity (narrow loops)
- Low core loss (narrow loops)
- Electric motors, transformers, switches, etc.

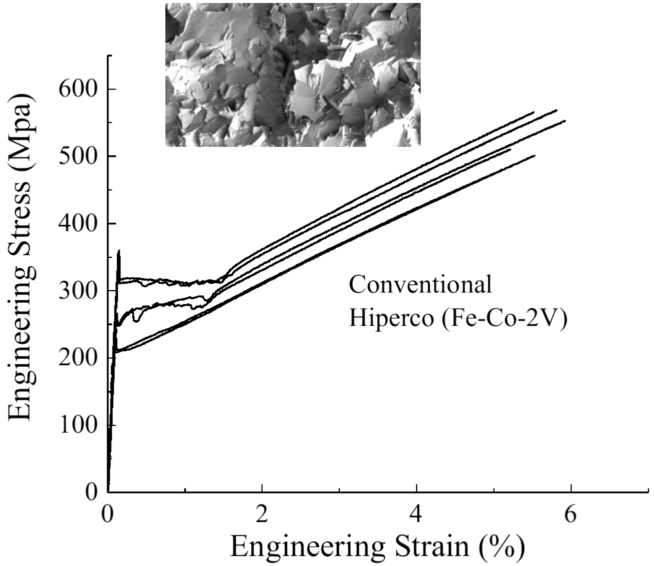


- However -

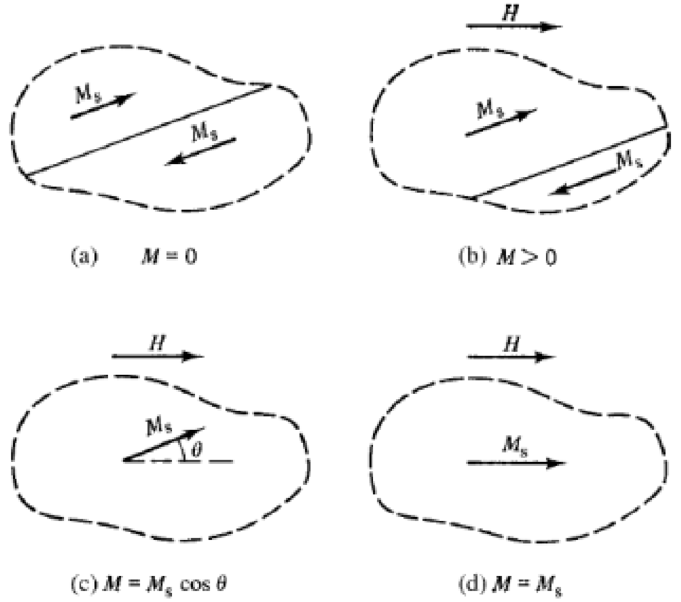
Poor mechanical properties:
- Result of ordered B2 and DO3 phase transformations
- Low yield strength
- Low ductility
- High notch sensitivity
- Low fracture toughness
- Low fatigue resistance

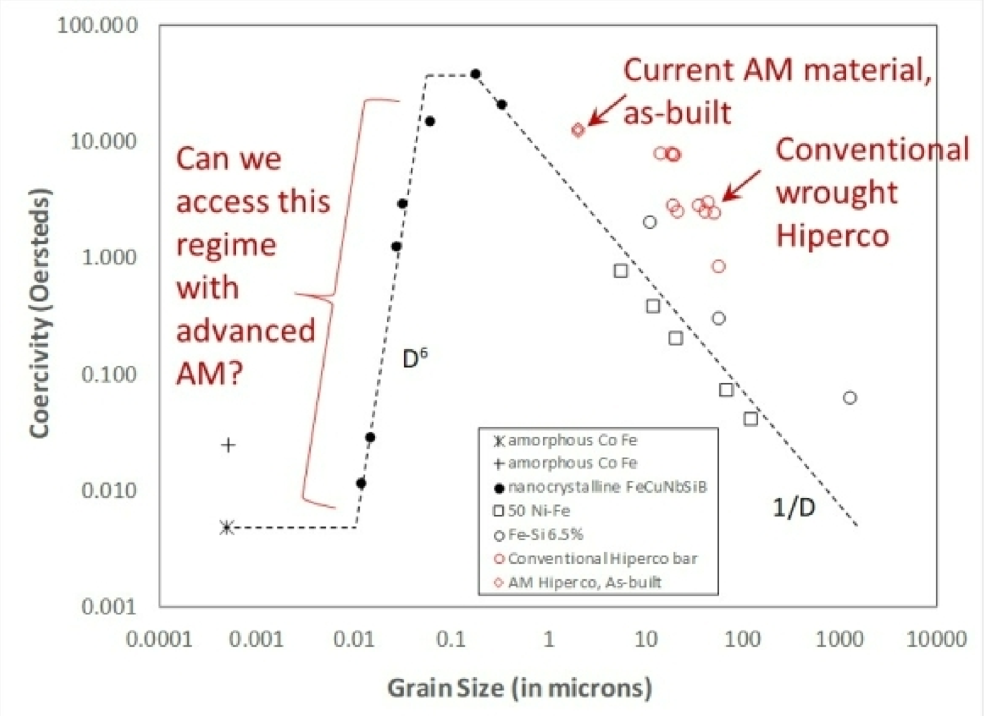
High silicon content electrical steel (Fe-6.5wt%Si)





Why these property tradeoffs?





Fundamental challenge: structural barriers (i.e., line and area defects, etc.) increase strength/ductility but inhibit microscale magnetization processes.

Grain size has strong effects:
If *D* = 0.1-1 micron, higher strength/ductility, harder magnetic properties.
If 0.1 > *D* > 1000 micron, decreasing strength/ductility, softer magnetic properties.
Conventional processing challenging/impractical to achieve D < 0.1 micron in bulk.

AM processing of advanced soft magnetic alloys – building on previous literature

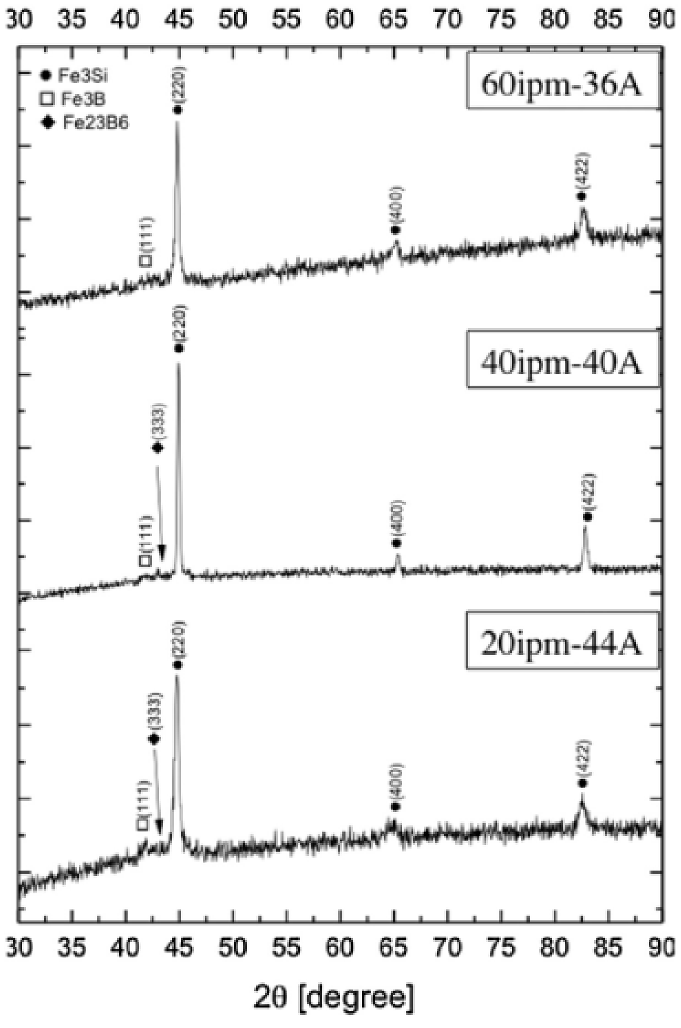
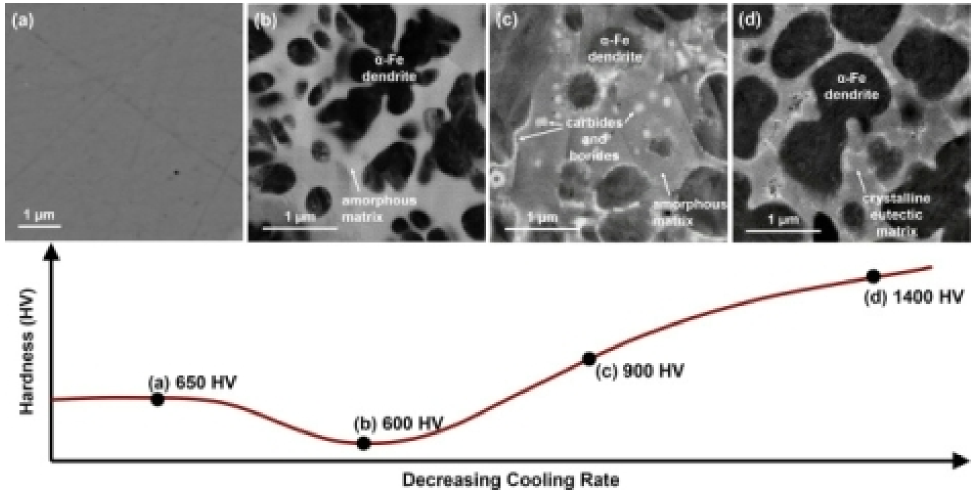


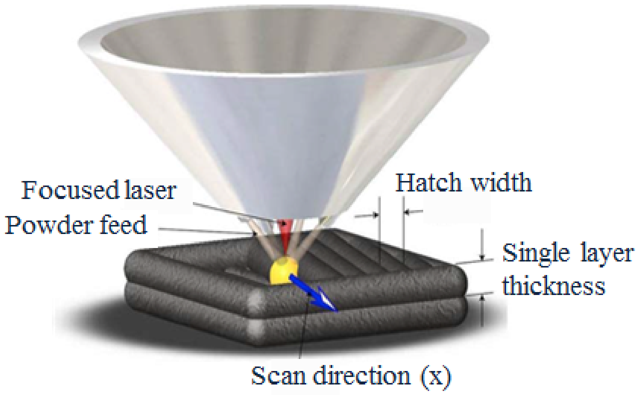
Fig. 2. XRD patterns of LENS™ processed FINEMET alloys.

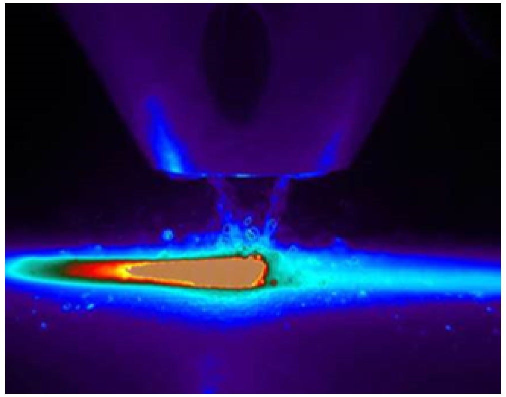
Conteri et al. (2017) "Laser additive processing of Fe-Si-B-Cu-Nb magnetic alloys," Journal of Manufacturing Processes, Vol 29, 175 – 181.

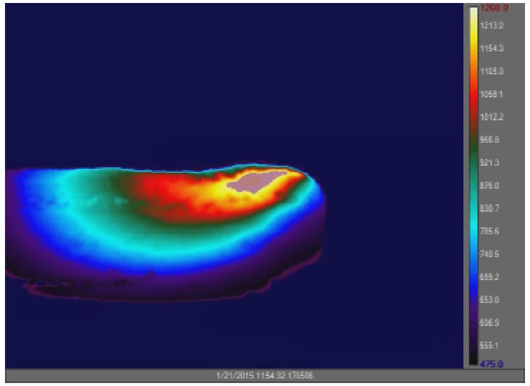


Bordeenithikasem, et al. (2021) "Controlling microstructure of FeCrMoBC amorphous metal matrix composites via laser directed energy deposition", Journal of Alloys and Compounds, Vol. 857, 157537

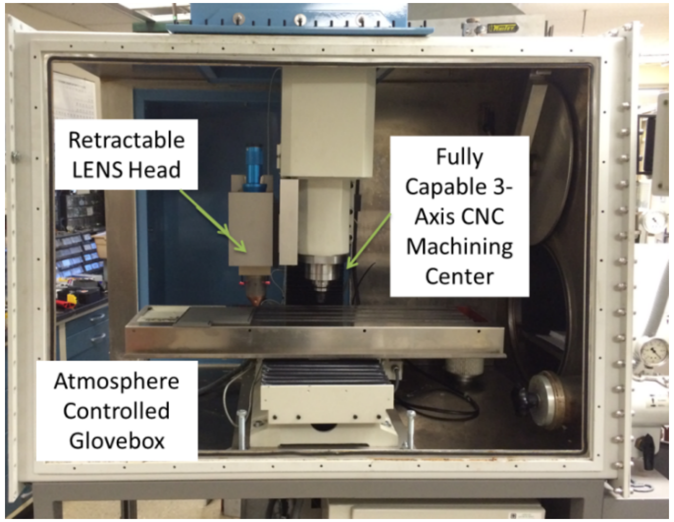
Laser beam directed energy deposition

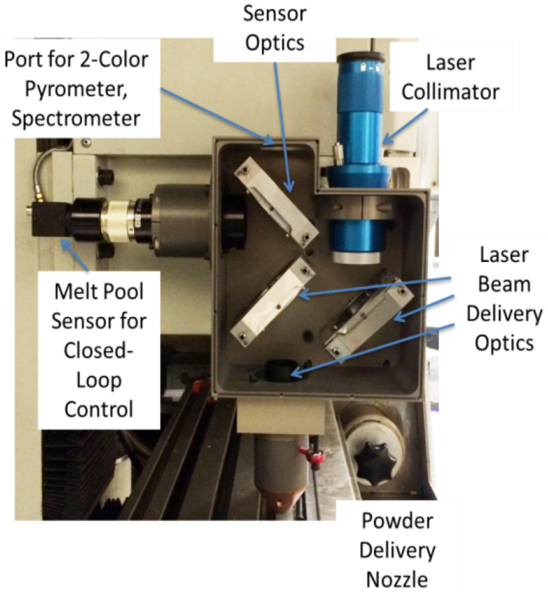






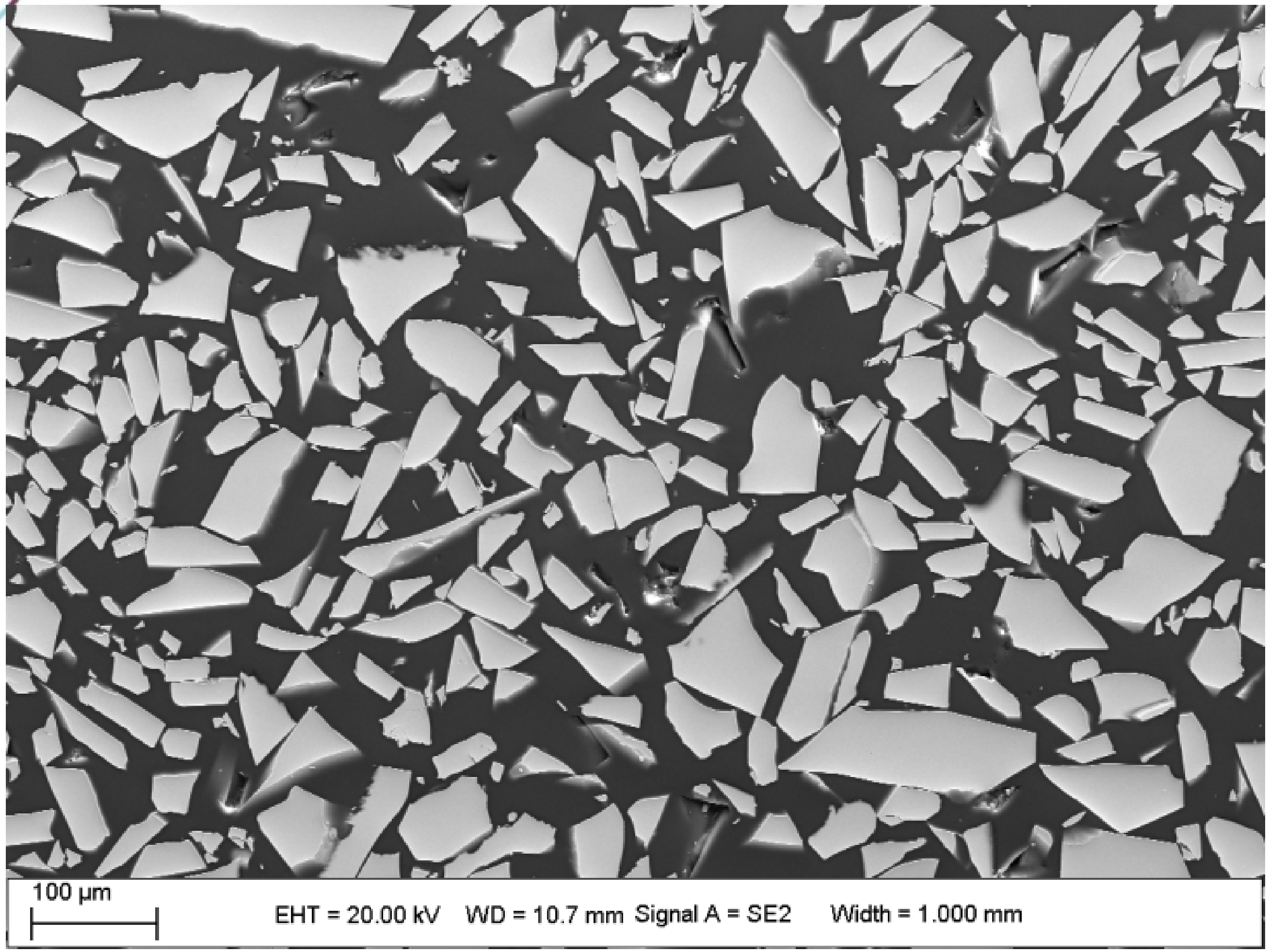
thermal history during bi-directional metal deposition



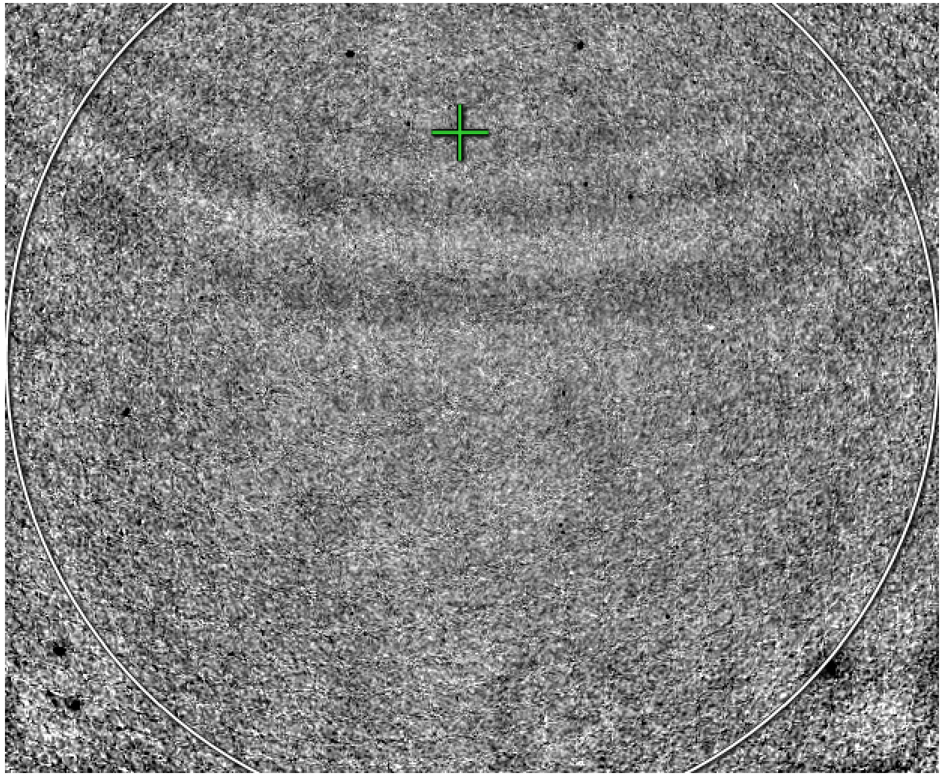


- Open architecture Laser Beam Directed Energy Deposition (LB-DED) apparatus for multi-material and custom alloy printing.
- 2-color pyrometer and FLIR cameras for in situ melt pool geometry and temperature measurements.
- High temperature heating platform for in situ stress-relief/annealing.
- Hybrid AM and subtractive processing.
- Controlled powder feed rate with up to 5 independent powder chemistries – enable in situ alloy design studies.

Powder feedstock – ball milled (amorphous) flakes



Provided by co-author Dr. Eric Theisen at Metglas



Target Alloy Composition:

- Fe = 83 wt %
- Si = 8.6 wt %
- Nb = 5.6 wt %
- B = 1.5 wt %
- Cu = 1.3 wt %

AM processing parameters

Produced thin-wall geometries

High relative density (>99%)

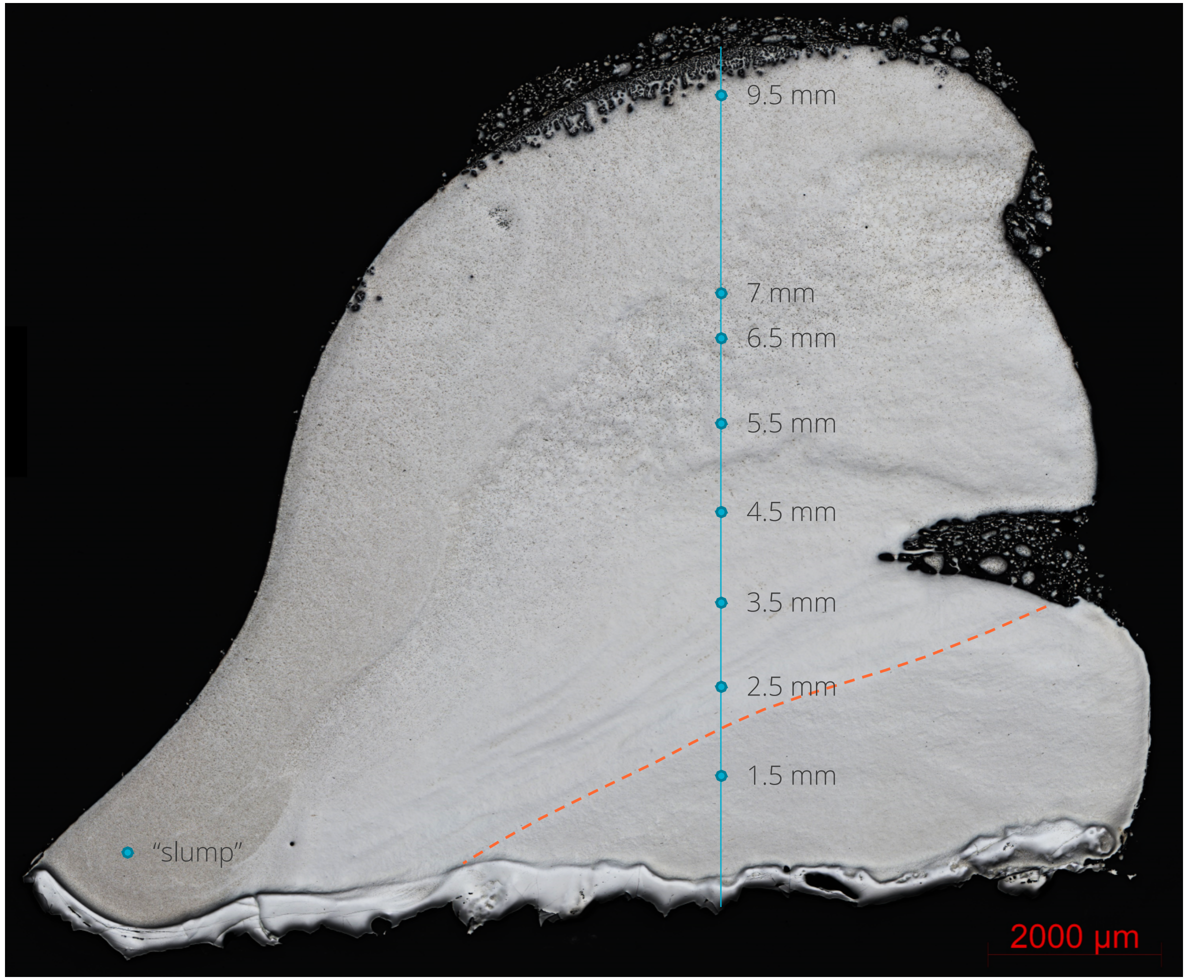
Laser Power: 400 W

Build Velocity: 450 mm/min

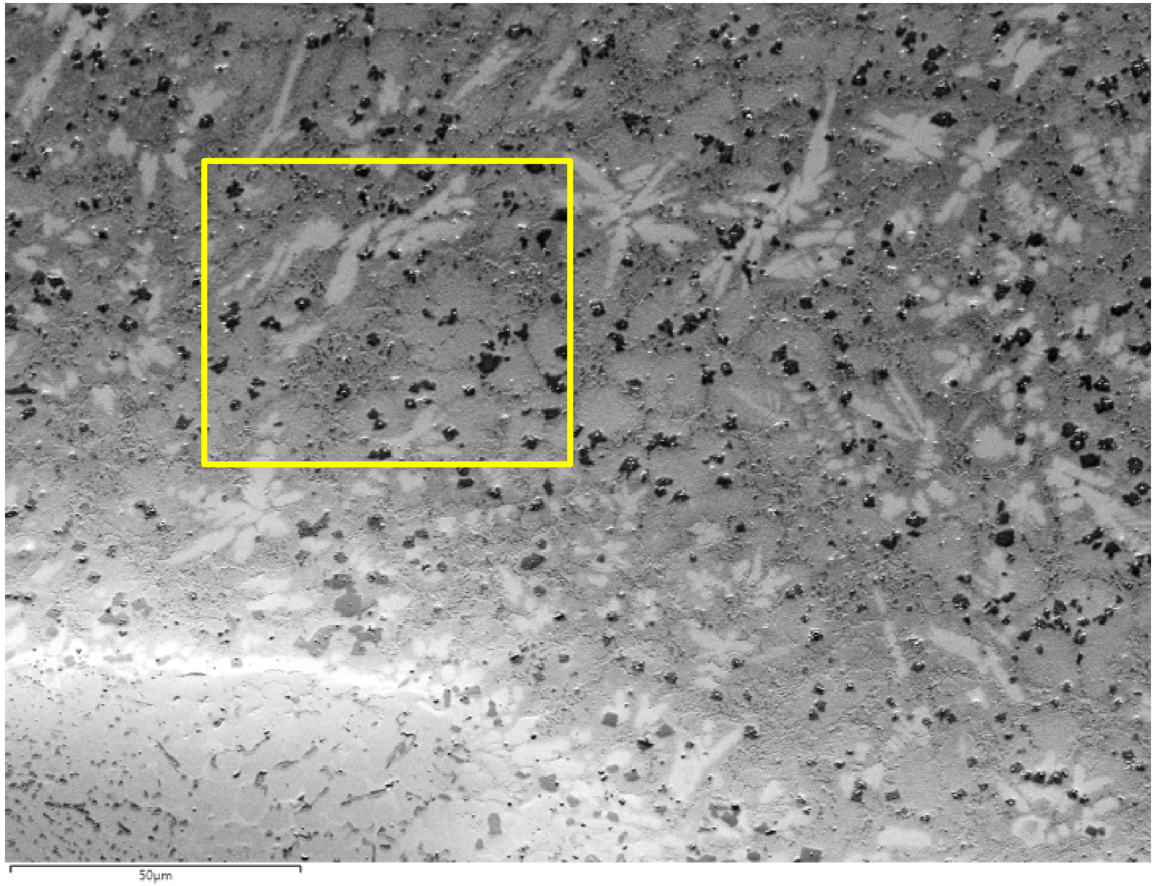
Substrate: Ti grade 2 (commercially pure Ti)

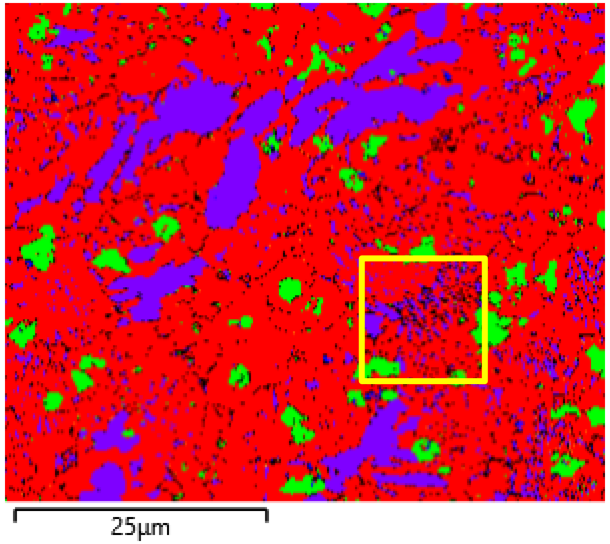
Was a nanocrystalline structure created??

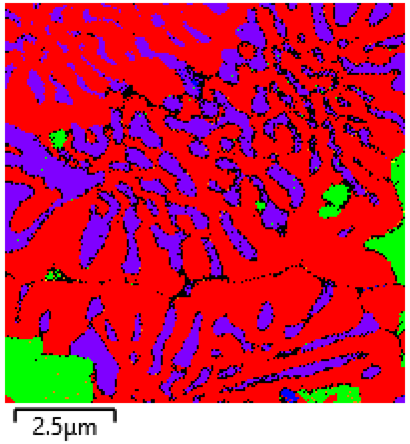
Regions for SEM analysis (named for distance from bottom)



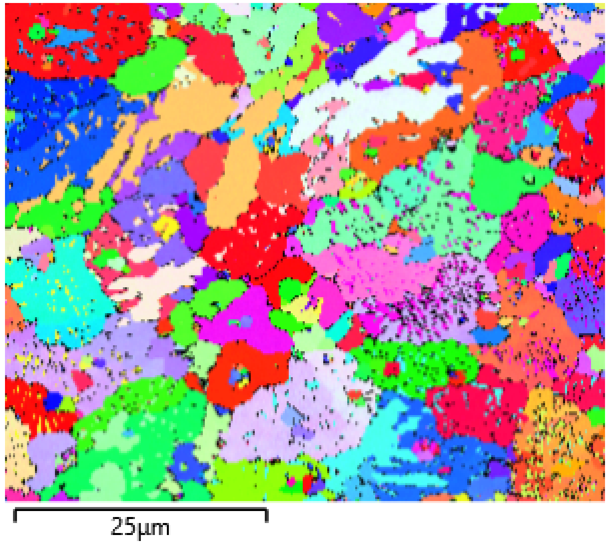
Near-bottom EBSD

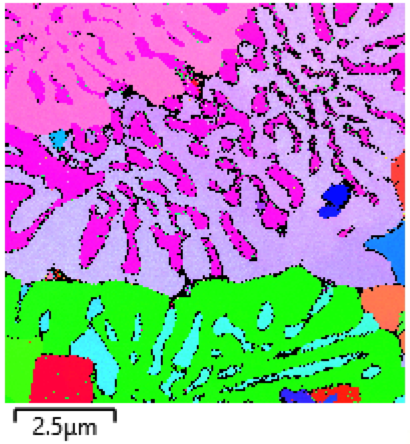




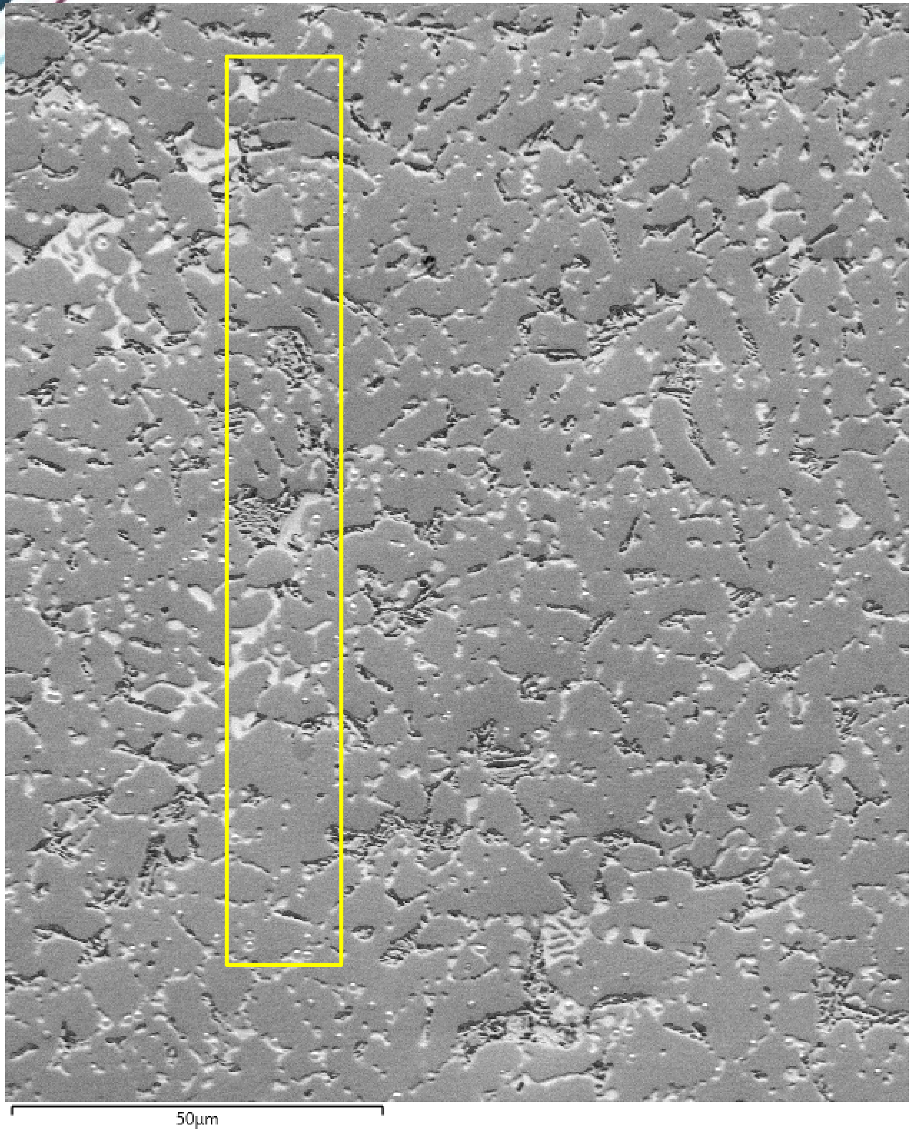


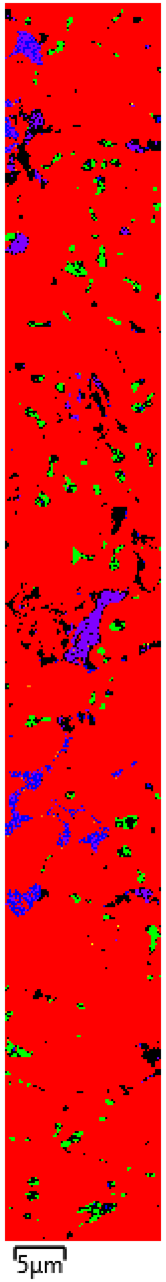
- BCC matrix
- Hexagonal $NbFe_2$ (Laves)
- Hexagonal B, Ti, Nb (could be $TiNbB_4$, TiB_2, or NbB_2)

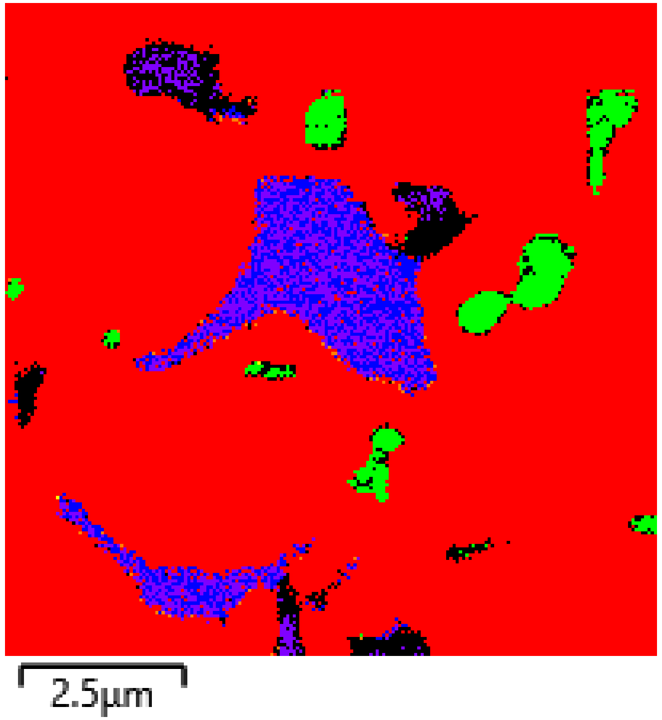




Near-top EBSD







- BCC matrix
- Hexagonal $NbFe_2$ (Laves)
- Hexagonal B, Ti, Nb (could be $TiNbB_4$, TiB_2, or NbB_2)

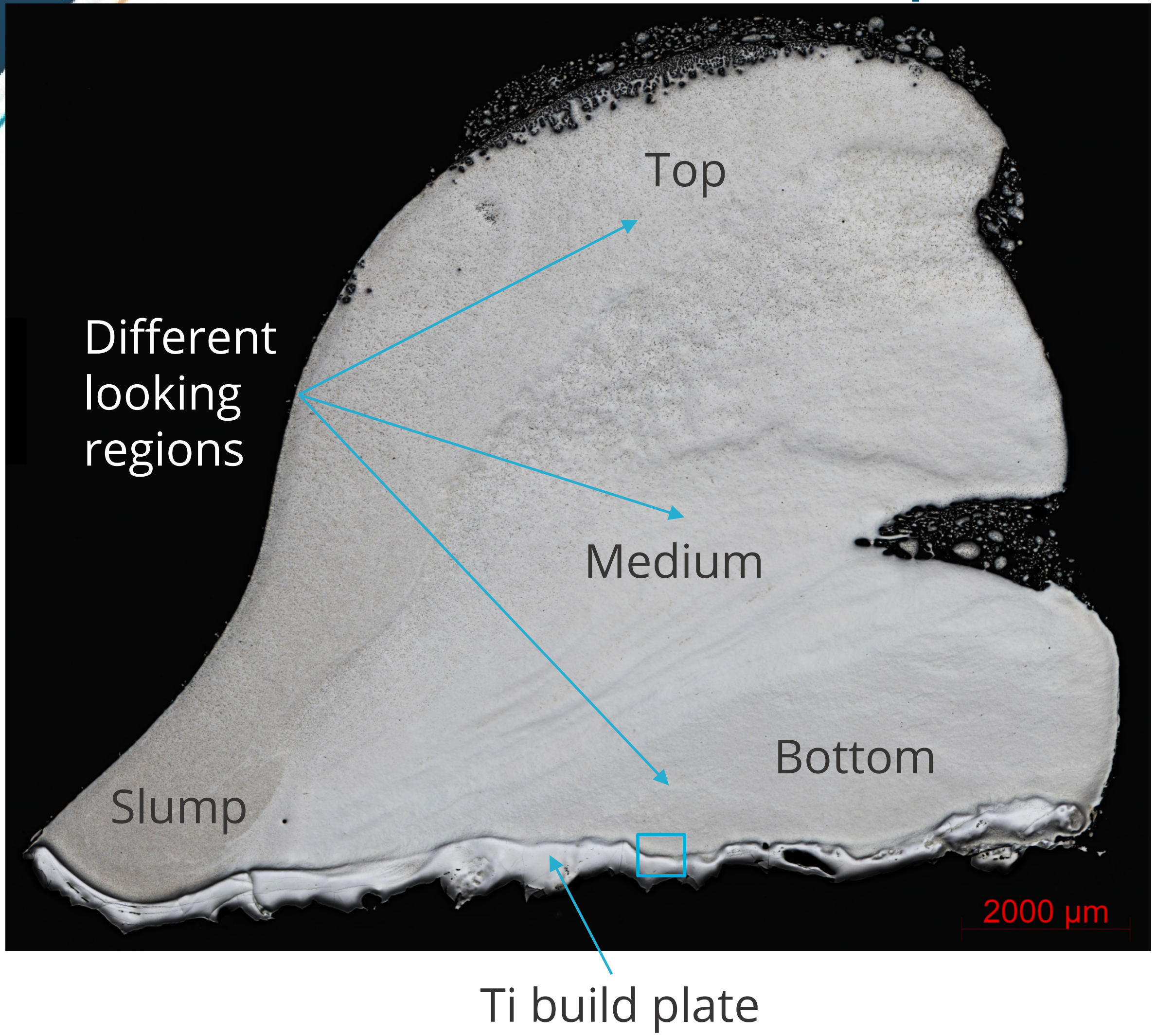
Was a nanocrystalline structure created??

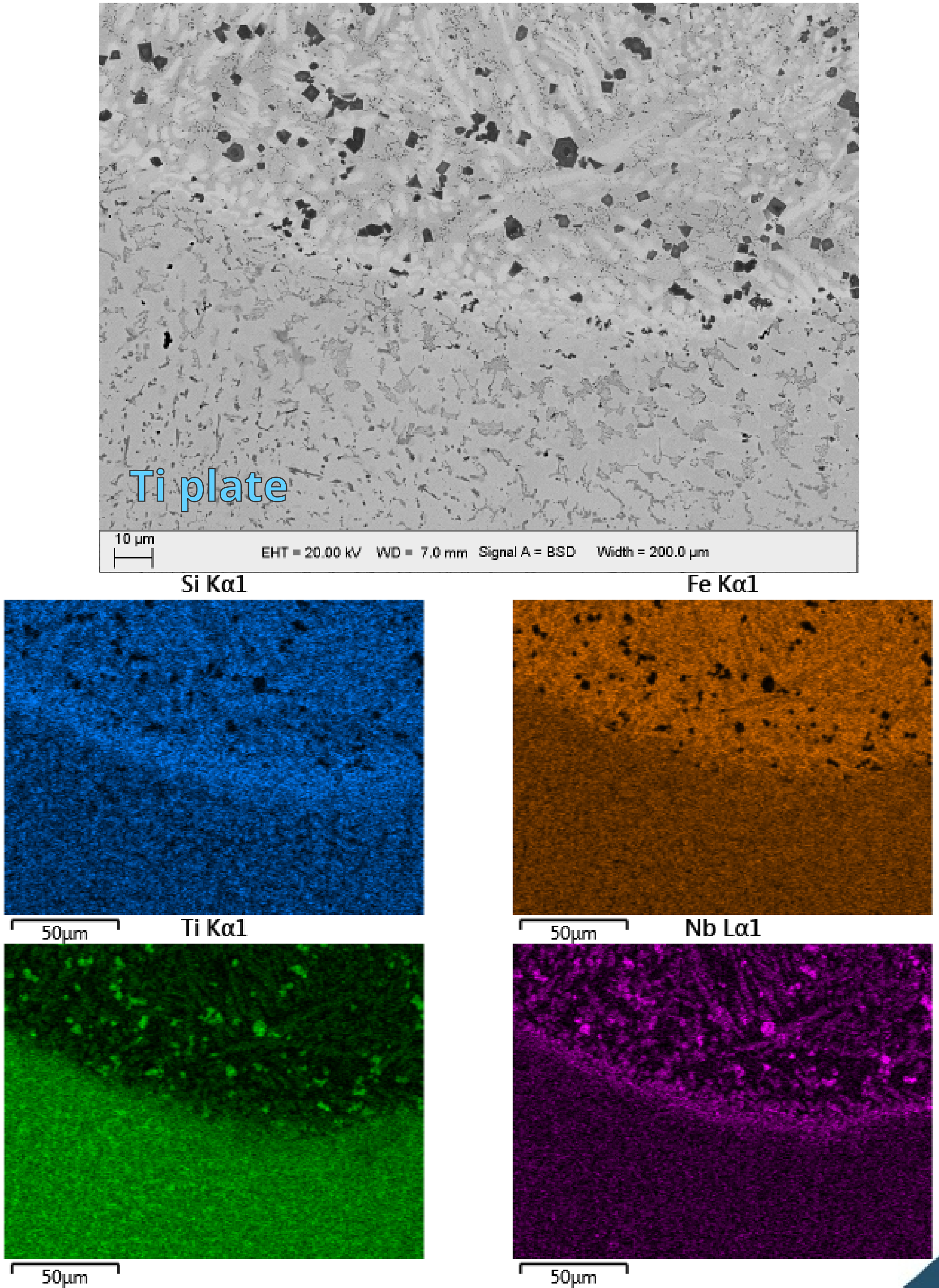
Coarse microstructure following DED.

Extent of bcc matrix phase increased with build height.

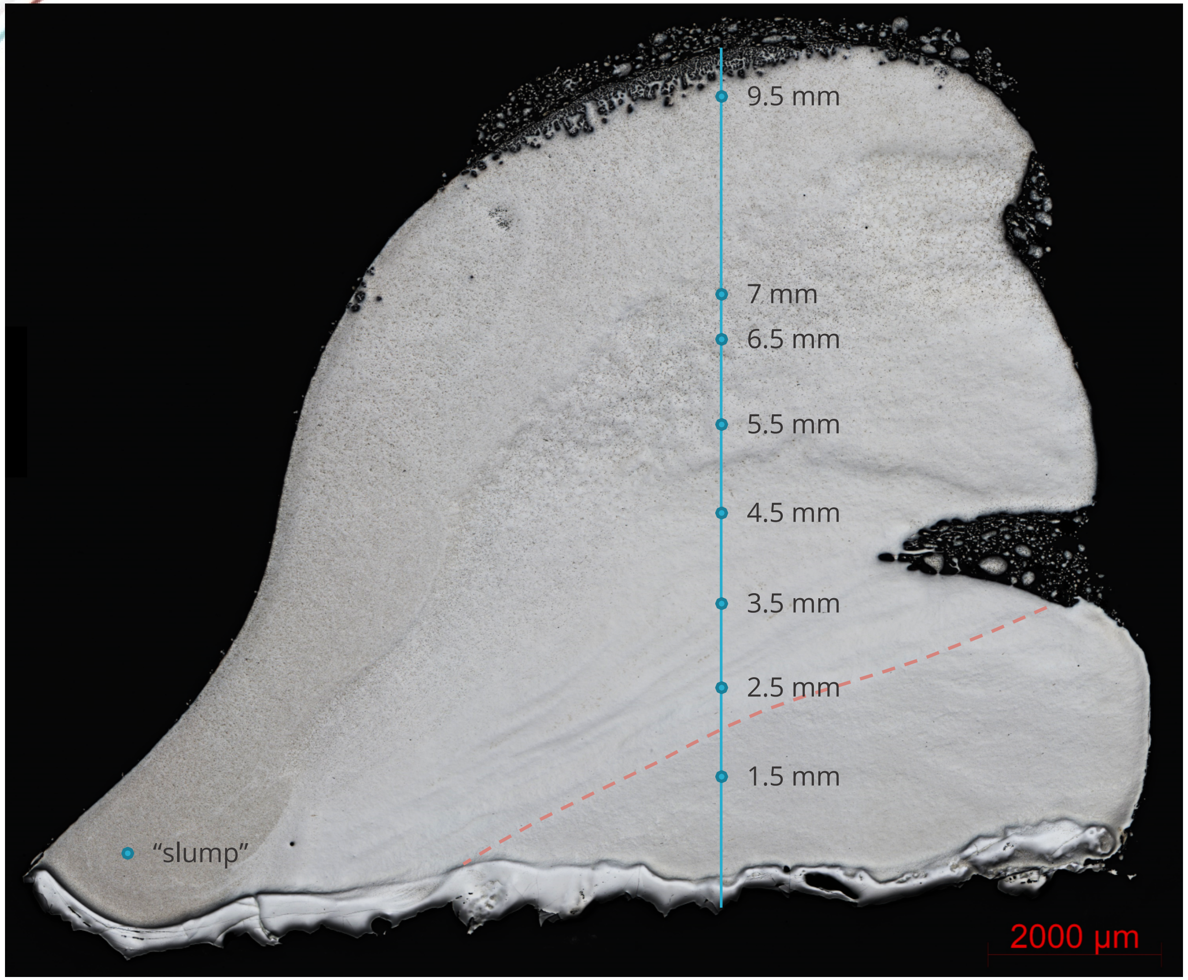
Characterization provides clues to grain structure…

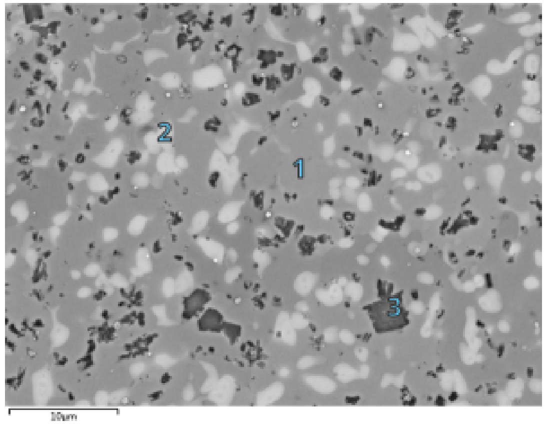
Interface with build plate

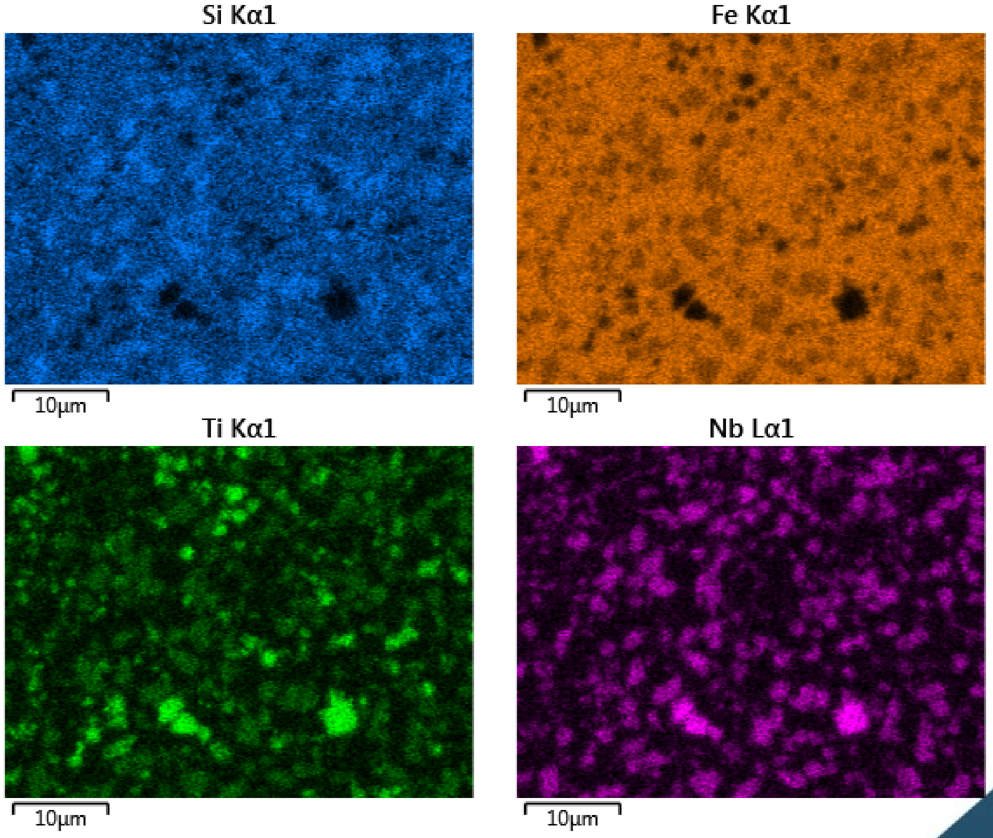




Bottom region – high Ti-content





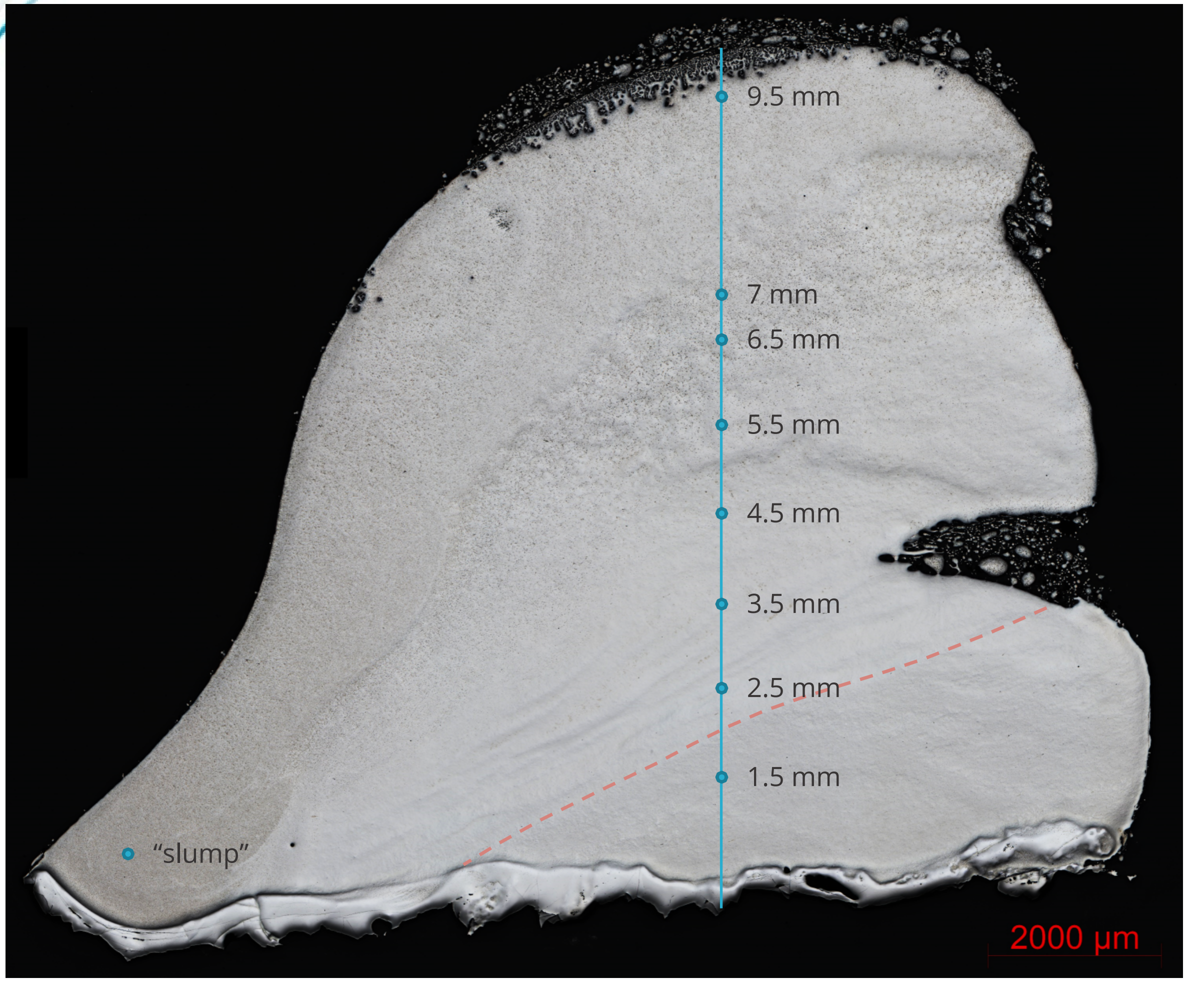


1: Matrix = Si & Fe

2: Bright Constituent = Nb, Si, Fe, & Ti (Fe in highest proportion)

3: Dark Constituent = Ti & Nb **+ B** (B in highest proportion)

Middle region: 2.5-5.5 mm build height

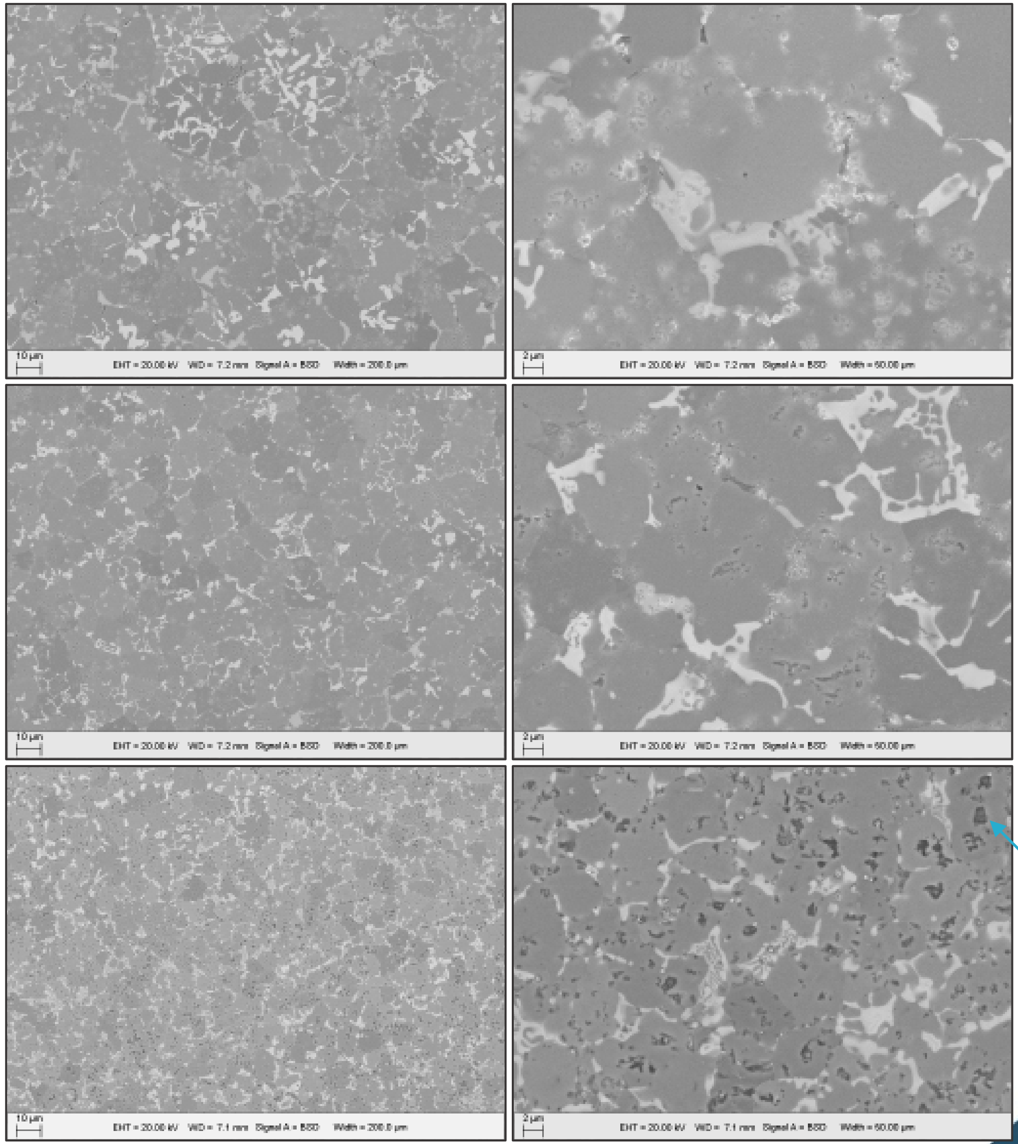


With increasing build height, microstructure coarsens (decreasing cooling rate) and amount of Ti-rich constituent decreases

5.5 mm

4.5 mm

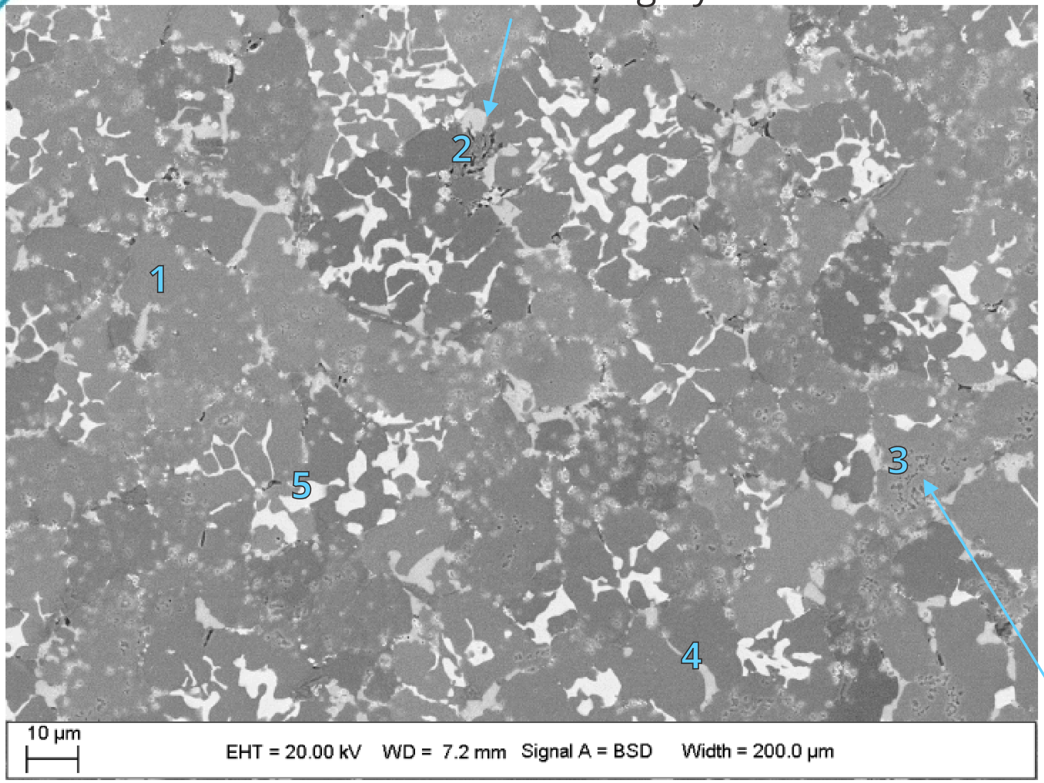
2.5 mm



Ti-rich constituent (darkest)

Middle region: 2.5-5.5 mm build height

This dark gray constituent is attached to “medium gray”



This dark gray constituent (Ti-rich) is within the matrix

1: Matrix = Si & Fe

2: Darkest gray = Fe & ? **+ B**

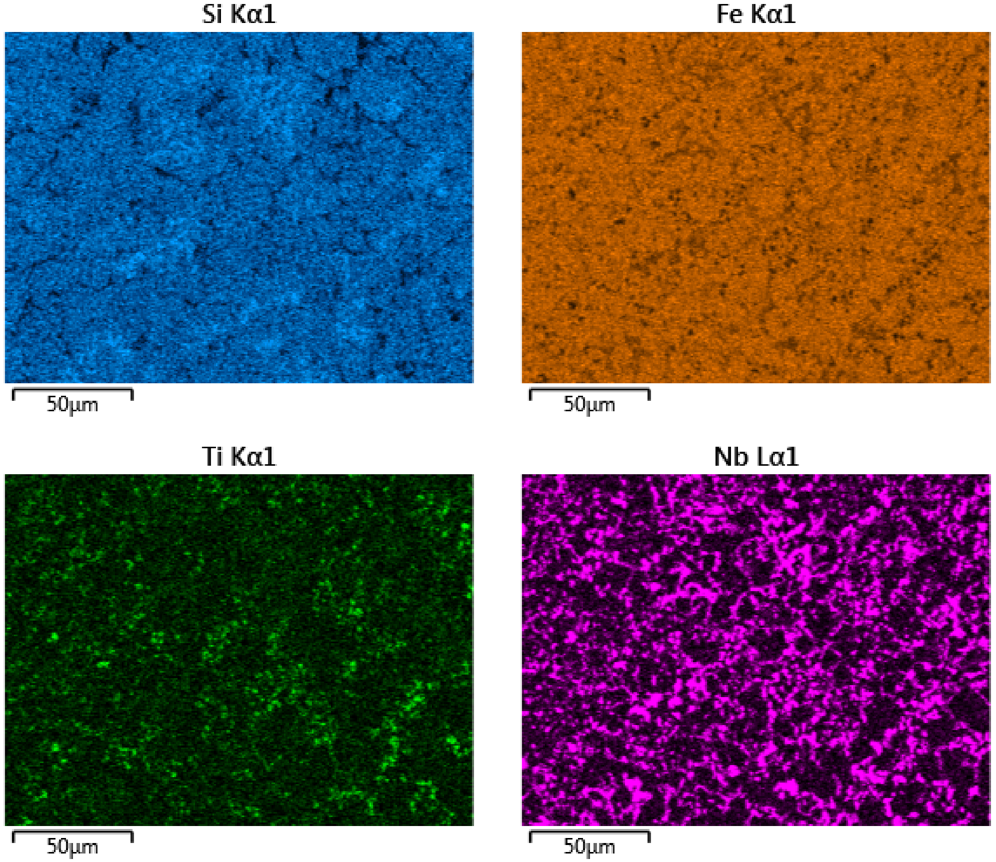
3. Other dark gray, Ti & Nb **+ B (B in highest concentration)**

4: Medium gray = Nb, Fe & Si ✓

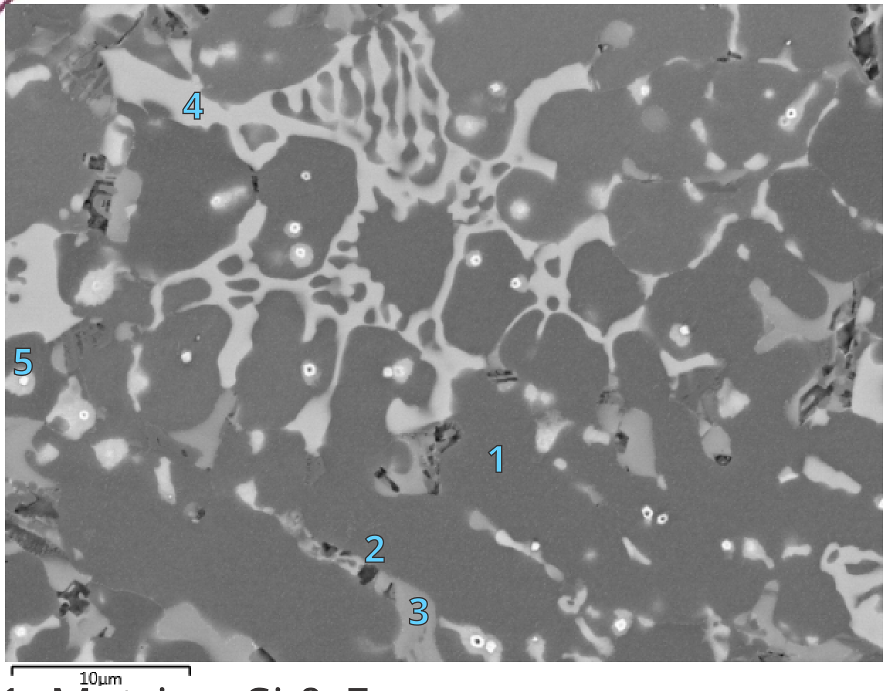
5: Bright = More Nb & Si, Less Fe ✓

<u>1st appearance of another dark constituent (labelled #2)</u>

- Always attached to “medium gray”
- As shown in coming slides, this new dark constituent contains Fe, but is depleted in all the rest of the mapped elements
- Since the BSE contrast is dark, suggests light elements
- Perhaps B-rich?



Top region – 9.5 mm



1: Matrix = Si & Fe

2: Darkest gray = Fe & ? **+ B**

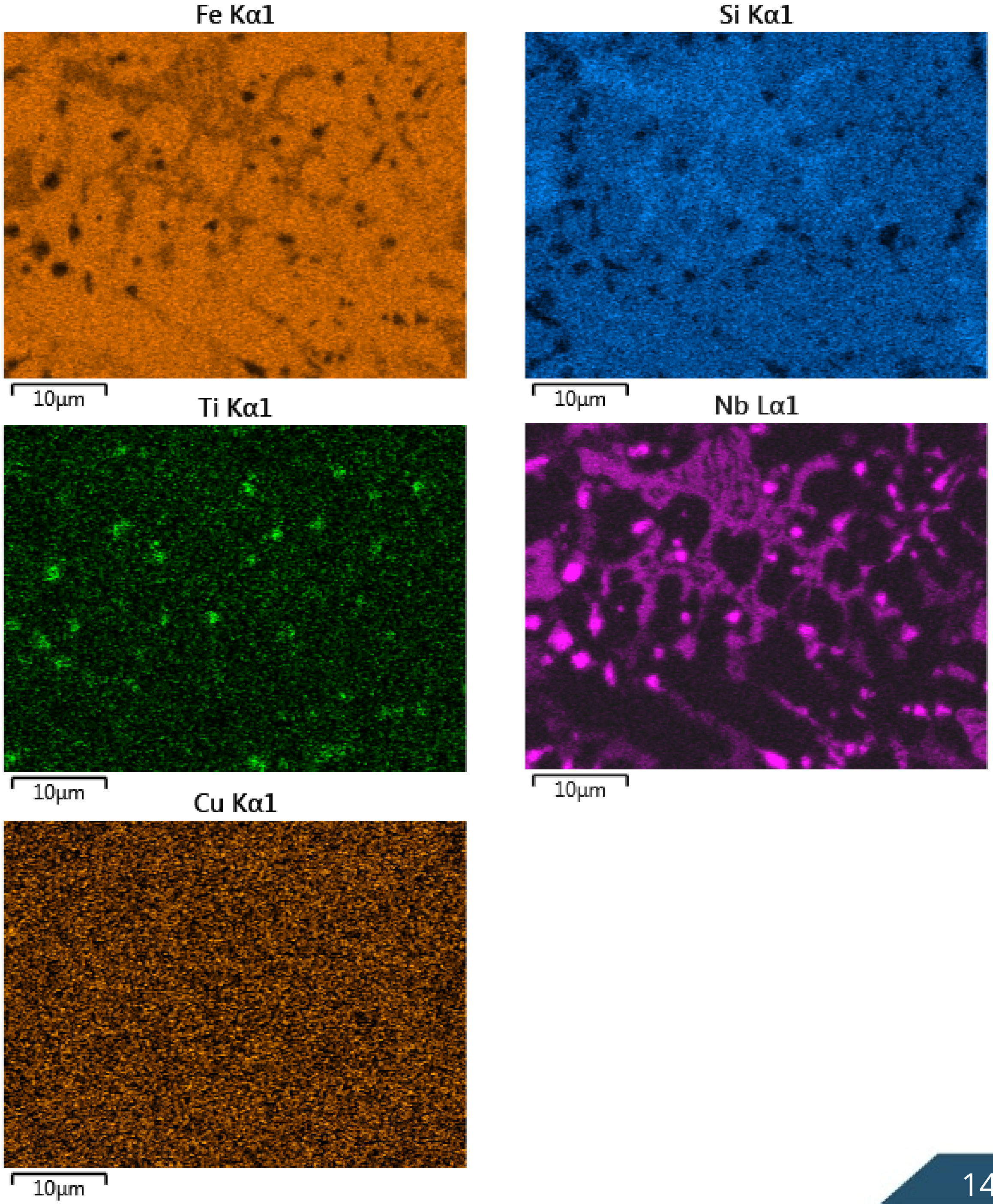
3. Medium gray = Nb, Fe & Si **+ B**

4: Light gray = More Nb & Si, Less Fe ✓

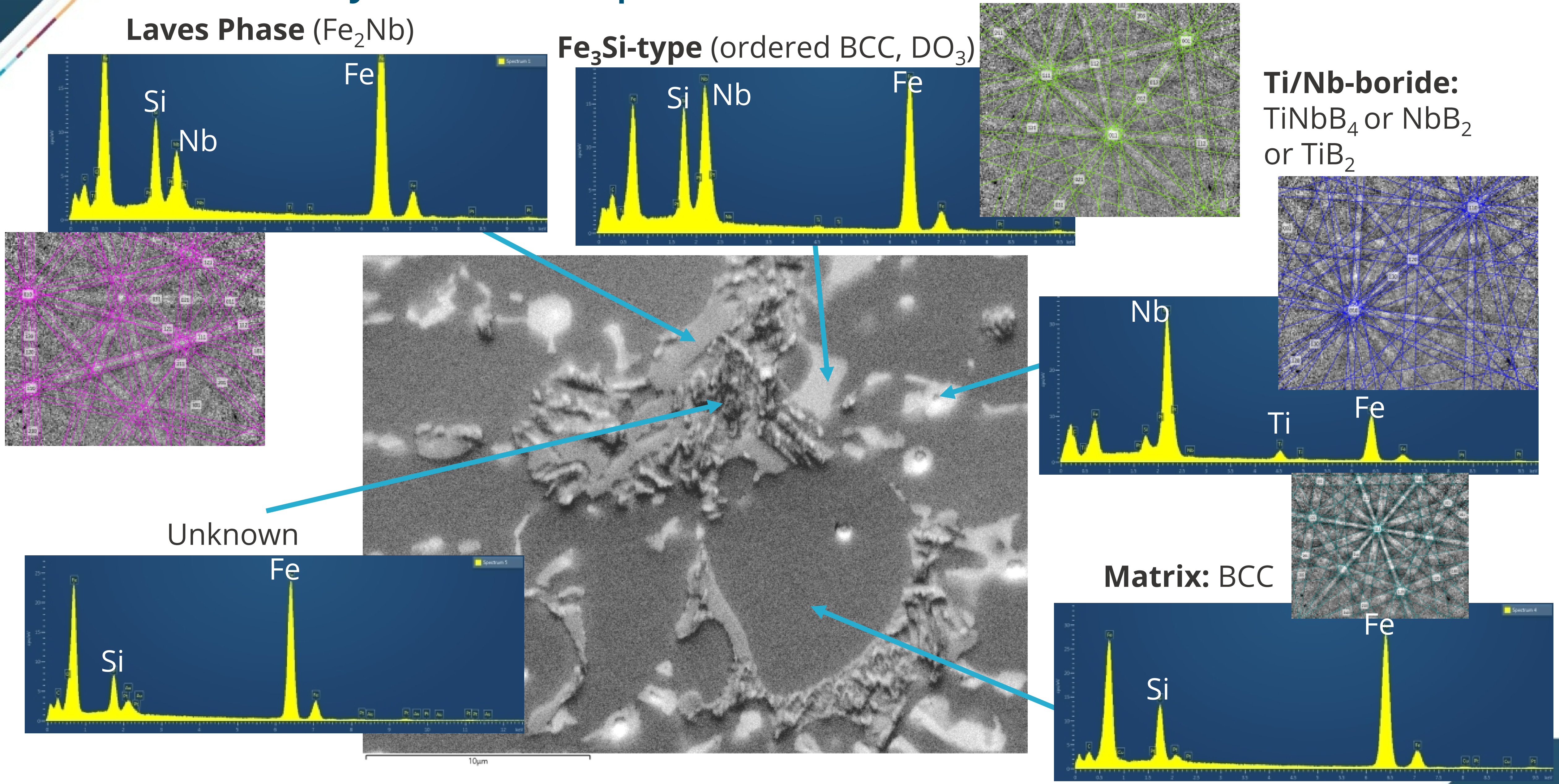
5: Bright spots = Nb & Ti **+ B** (this is where the most B is in this region)

***4 & 5 are sometimes indistinguishable in BSE**

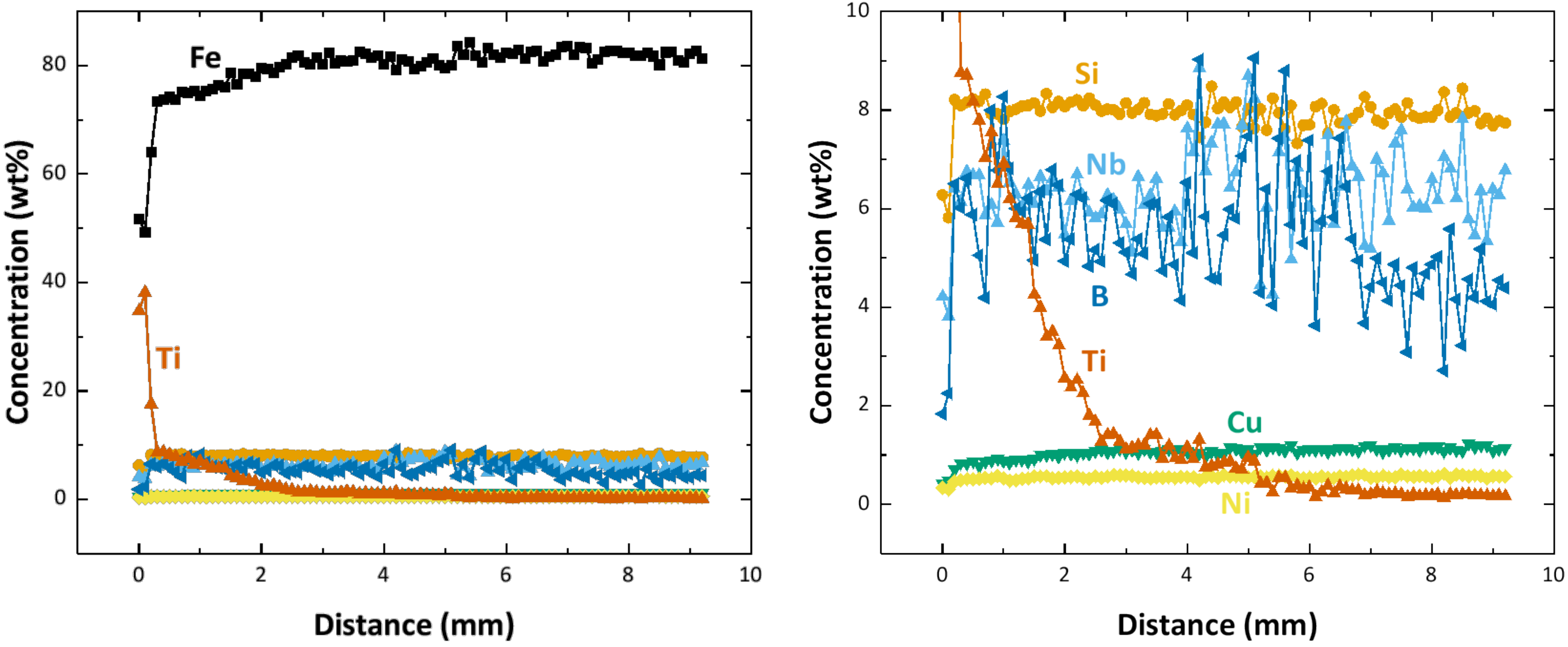
Main difference here is lack of Fe & Si in these regions



Summary of observed phases

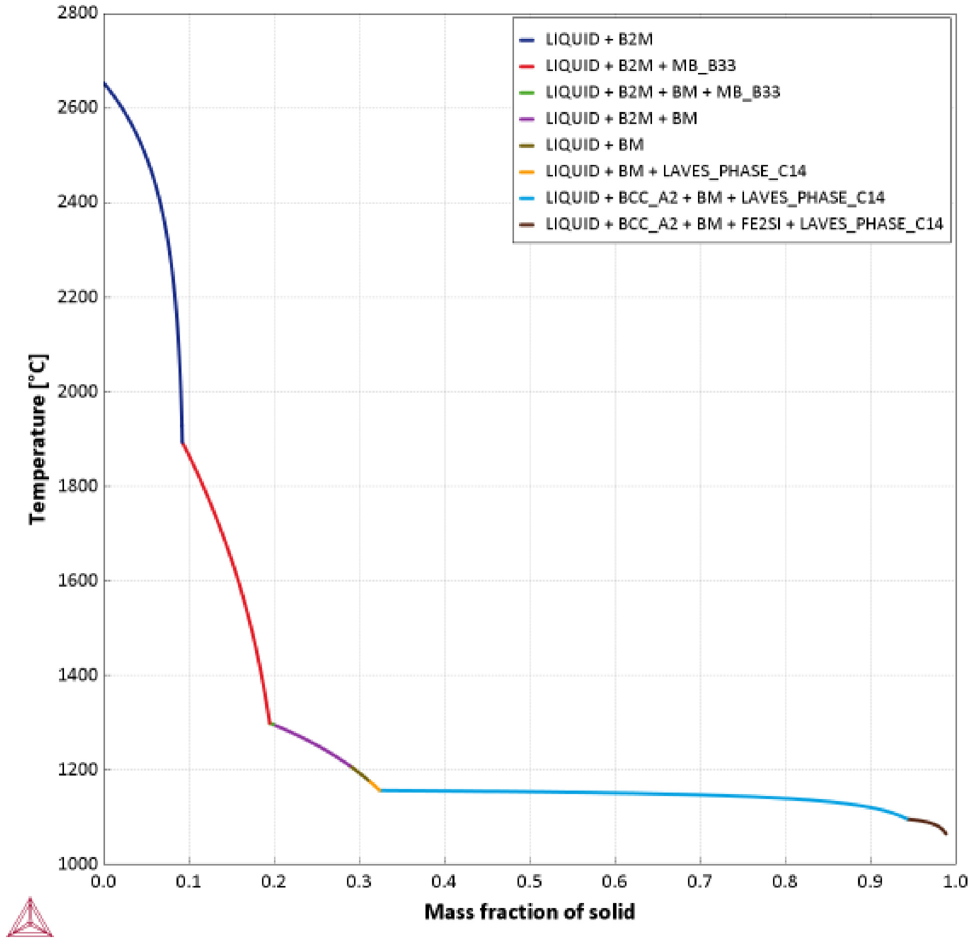


Wavelength dispersive spectroscopy of entire build

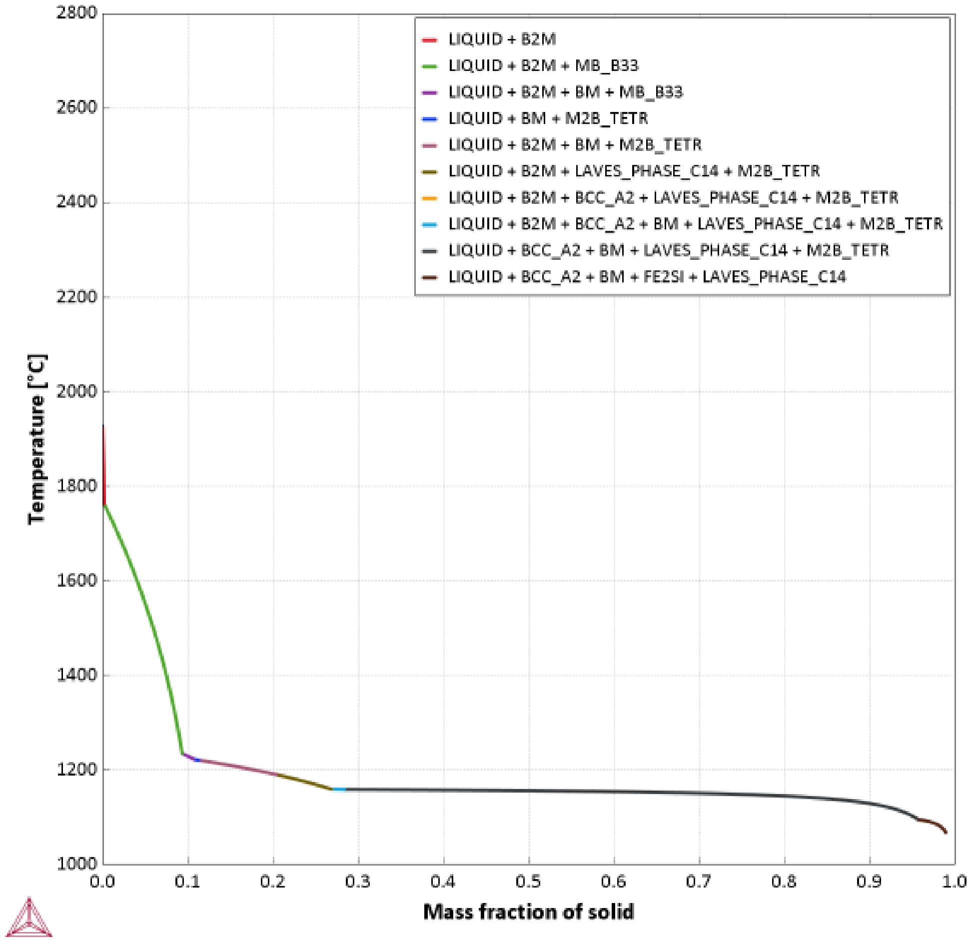


Thermo-calc Scheil Solidification Analysis

Bottom (Ti-rich) composition (In wt %):
70% Fe, 7.4% Si, **6.5% Ti**, 6.9% Nb, 0.8% Cu, 0.5% Ni, 7.8% B



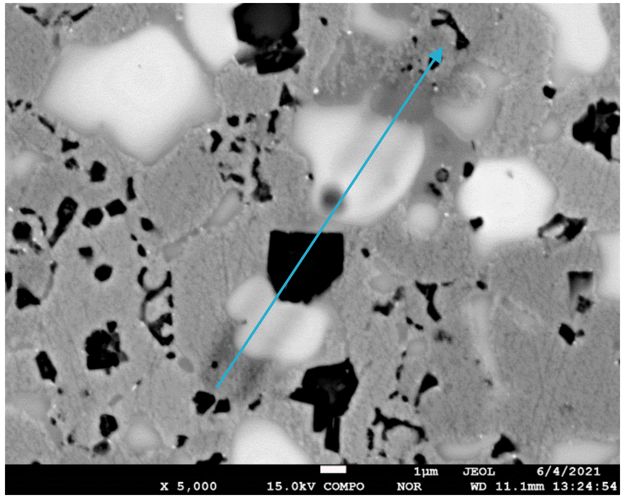
Top composition (In wt %):
80% Fe, 7.7% Si, **0.2% Ti**, 6.2% Nb, 1.1% Cu, 0.2% Ni, 4.6% B

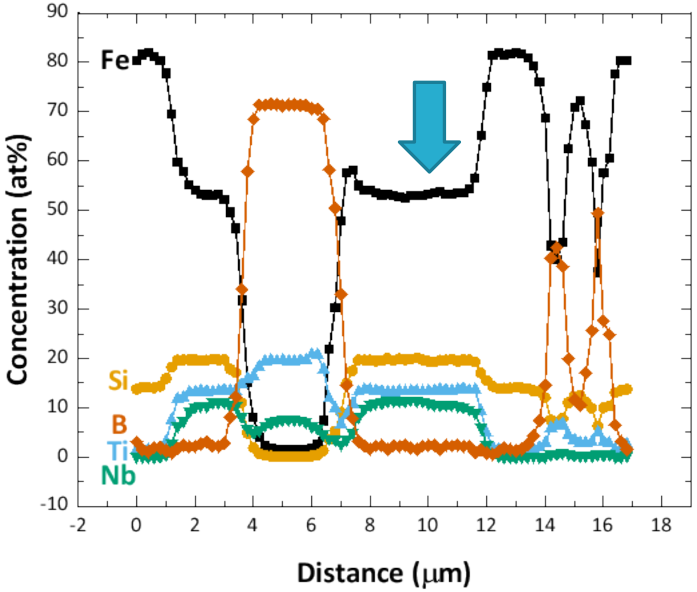


B2M = Ti_2B
MB_B33 = $(Fe,Ti,Nb,Ni)_1(B)_1$ – so a MB boride
BM = $(Fe,Ti)_1B_1$ – a different composition MB boride
LAVES_PHASE_C14 = $(Fe,Si,Ti,Nb,Cu,Ni)_2(Fe,Si,Ti,Nb,Cu,Ni)_1$ – the hexagonal C14 type Laves phase, Fe_2Nb
M_2B_TETR = $(Fe,Ni)_{0.67}(B)_{0.33}$

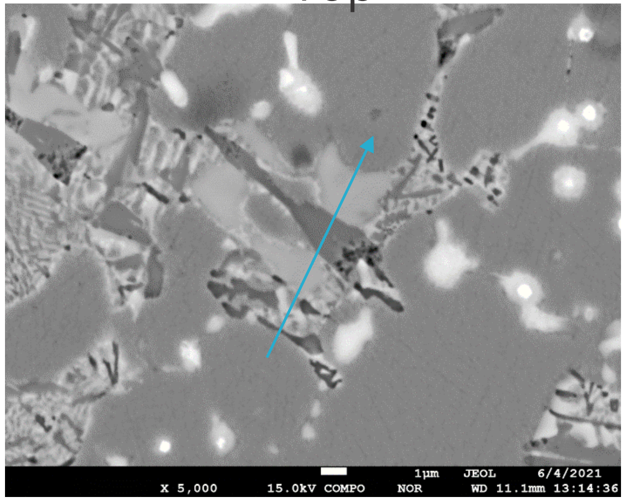
Lave phase throughout sample is similar

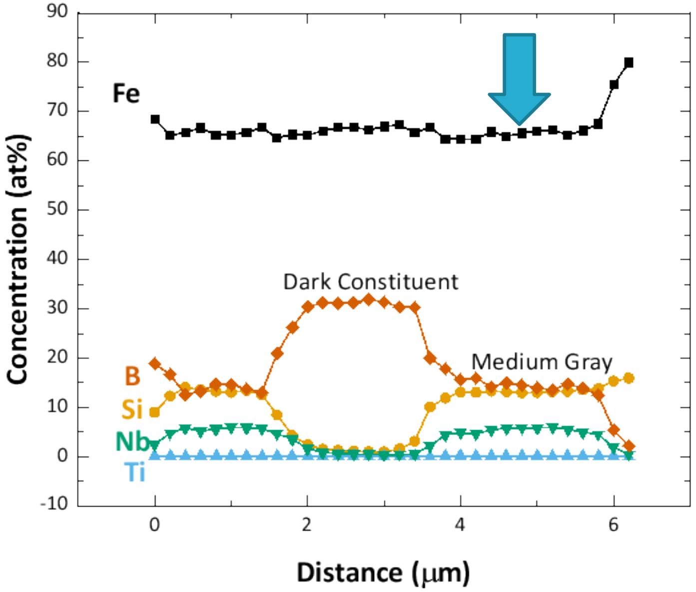
Bottom



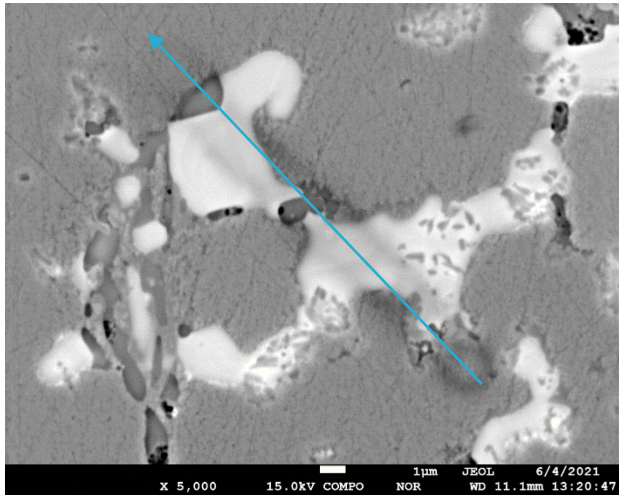


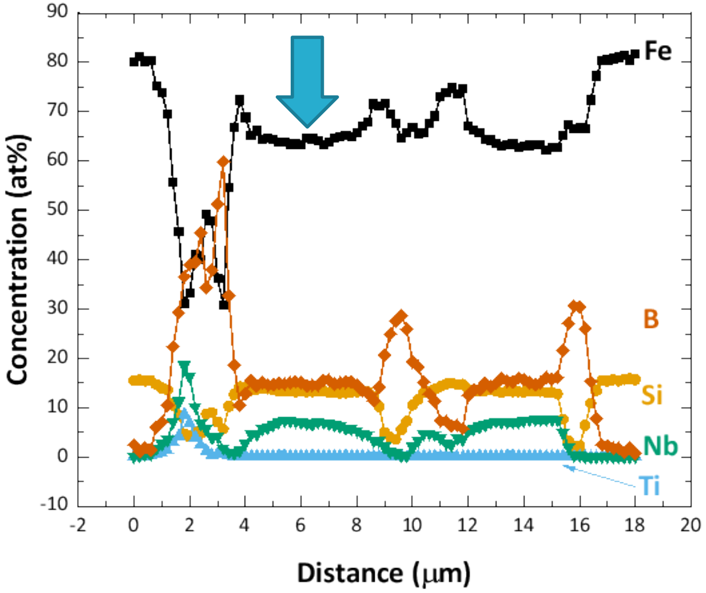
Top





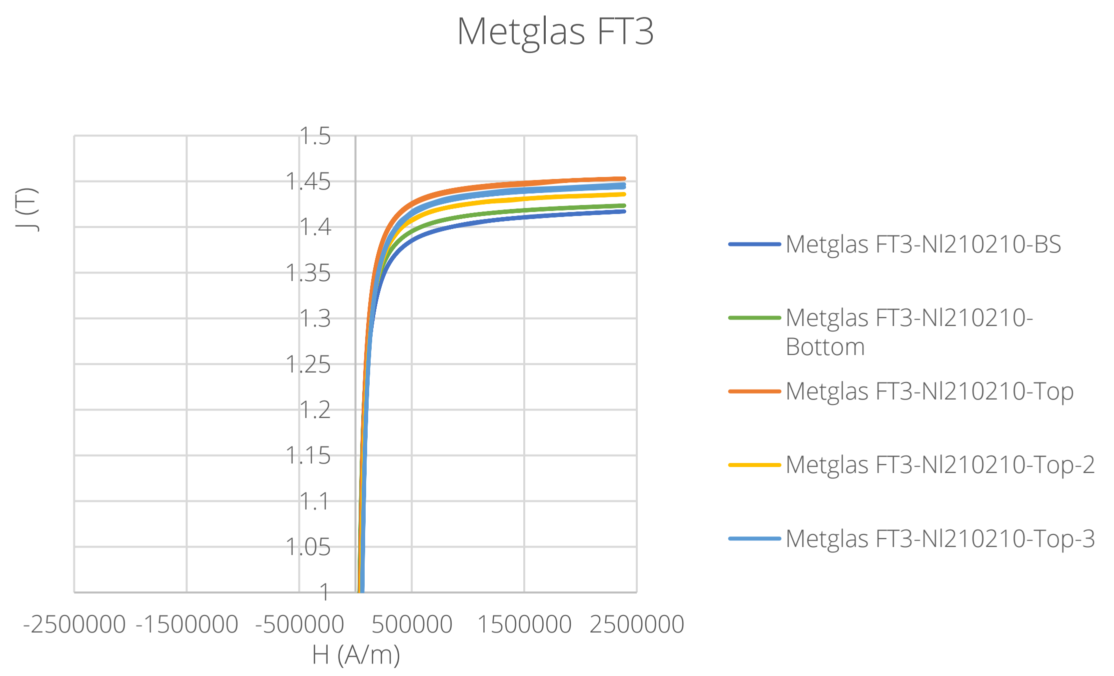
Middle





Magnetic Properties (VSM measurement)

Sample ID	Volume (m³)	Density (g/cm^3)	mass (g)	Msat (AVG) (A/m)	Jsat (AVG) (T)	Coercitivity (AVG) (A/m)	Susceptibility Average	Permeability Average
Metglas FT3-NI210210-BS	2.00E-09	7.53E+00	1.50E-02	1.09E+06	1.37E+00	4.55E+02	37.57	38.57
Metglas FT3-NI210210-Bottom	2.00E-09	7.51E+00	1.50E-02	1.10E+06	1.38E+00	3.85E+02	36.47	37.47
Metglas FT3-NI210210-Top	2.83E-09	7.67E+00	2.17E-02	1.16E+06	1.45E+00	4.13E+02	25.88	26.88
Metglas FT3-NI210210-Top-2	3.56E-09	7.65E+00	2.72E-02	1.14E+06	1.44E+00	4.14E+02	19.46	20.46
Metglas FT3-NI210210-Top-3	4.14E-09	7.66E+00	3.17E-02	1.15E+06	1.44E+00	4.27E+02	16.79	17.79



Summary

1. Printed a novel customized FeSiNbBCu soft magnetic alloys from milled powder-like flakes using LB-DED processing

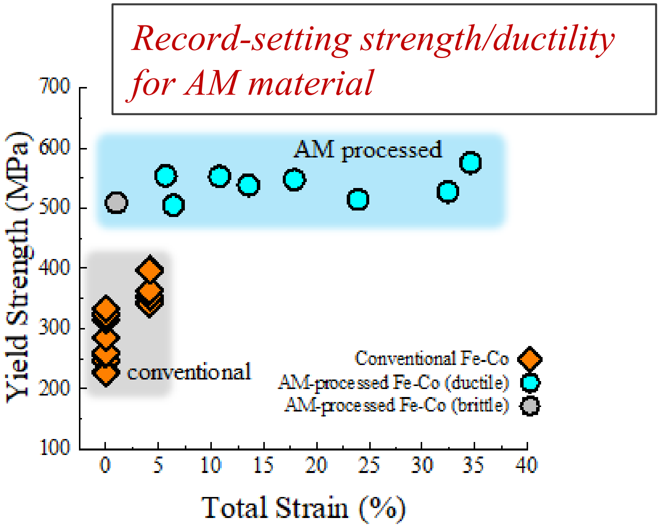
2. Microstructure had coarse grain size with up to five distinct phases

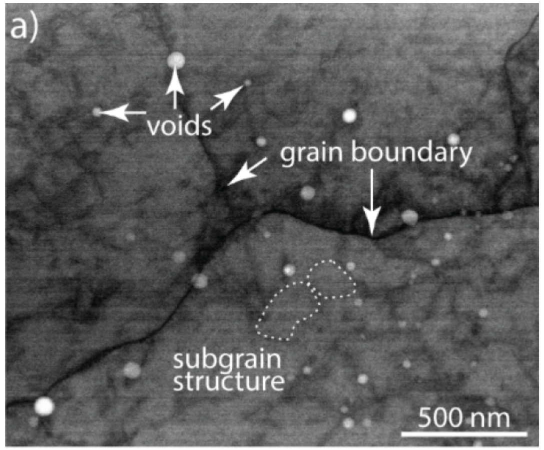
3. Ti "contamination" was observed throughout build height due to gettering of the B-content; forming (Ti,Nb) boride precipitates – need to consider build plate material!

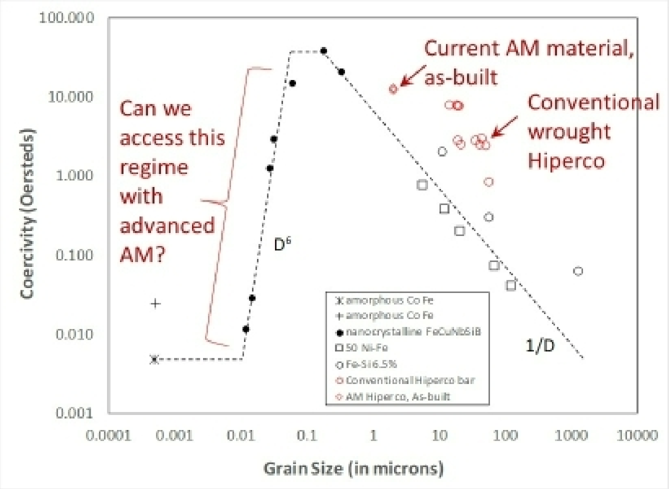
4. Resultant microstructure phase evolution was supported by Thermcalc predictions

5. Magnetic properties we slightly impacted by varying Ti-content, most notably the full-field induction and relative permeability values; the former decreasing and the latter increasing with increased Ti.

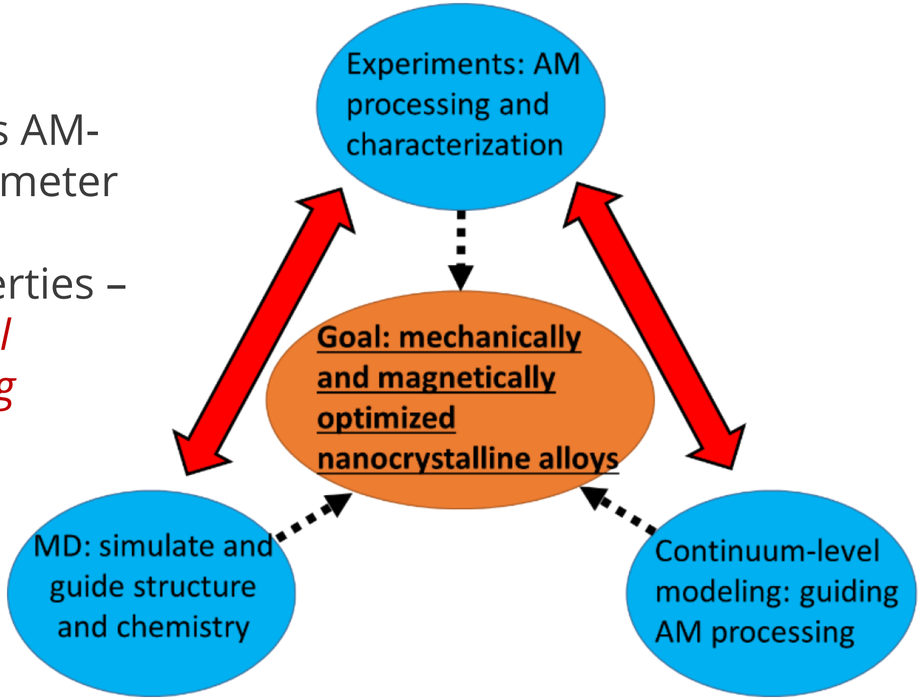
Project purpose and objectives



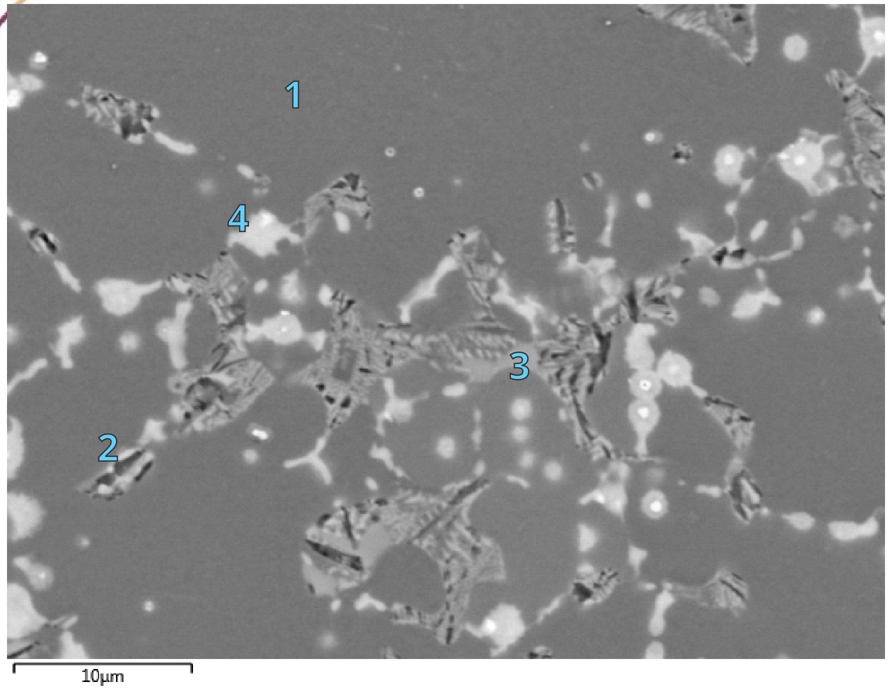


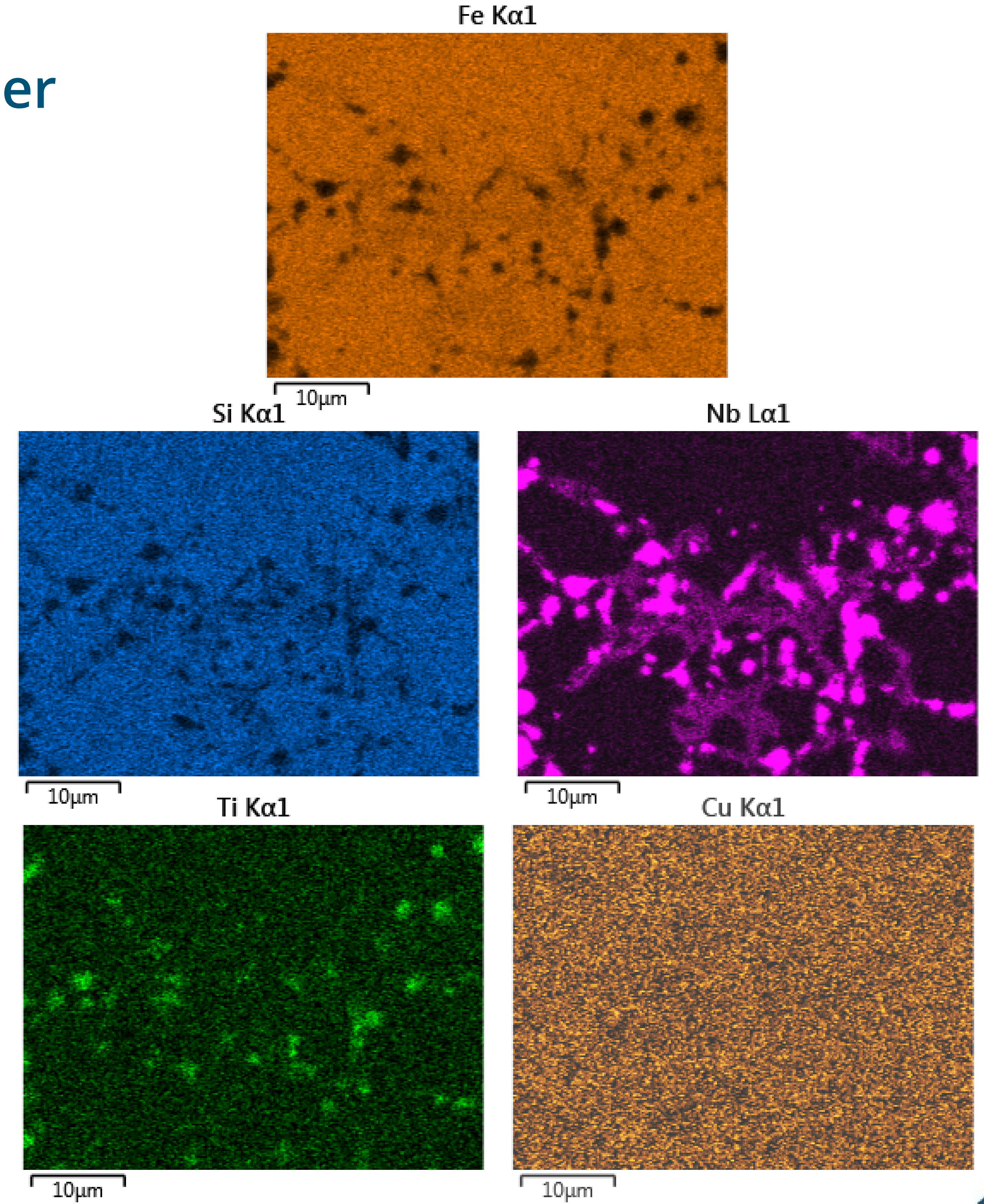


Previous research suggests AM-enabled hierarchical (nanometer -to-micrometer) structures enhance mechanical properties – *route to improve mechanical properties without sacrificing magnetic performance?*



Top region – 7.5mm and higher





1: Matrix = Si & Fe

2: Dark = Fe & ?

3: Medium Gray = Fe, Si, & Nb

4: Bright = Nb & Ti