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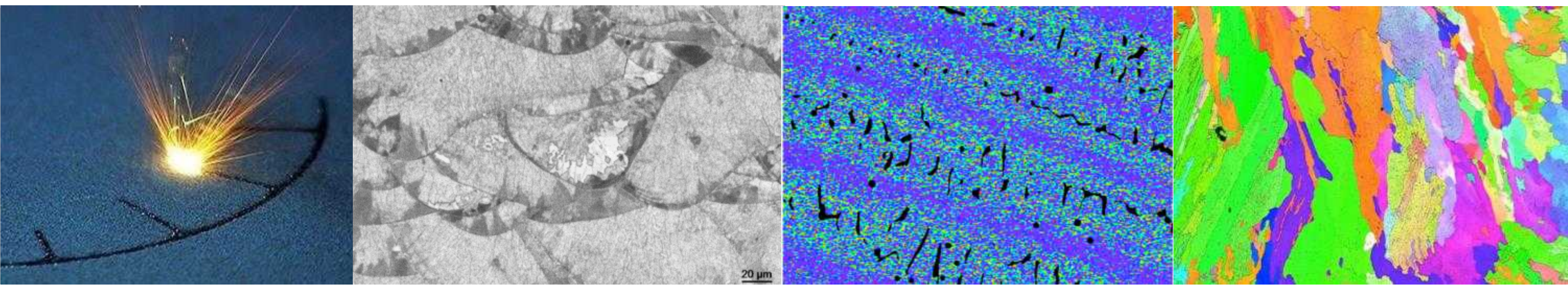

Microstructural Characterization of Laser Welds on Additively Manufactured Metal Components

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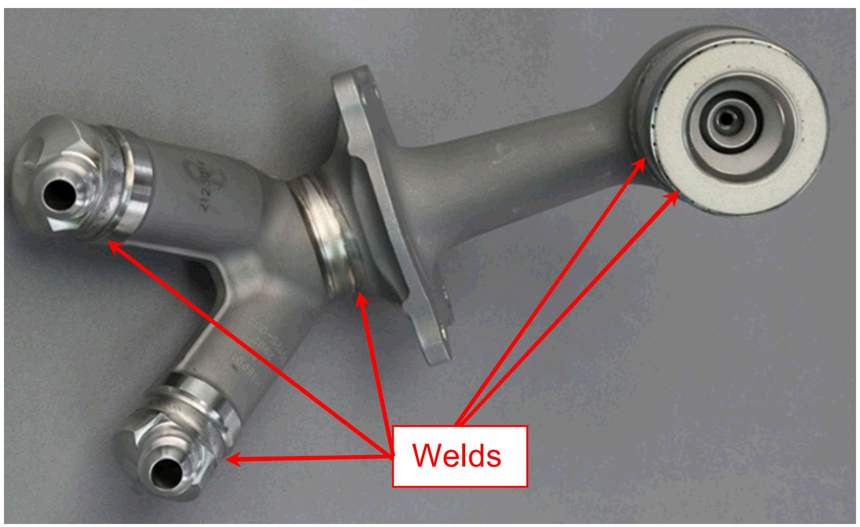
Why Examine the Weldability of Metal AM Components?

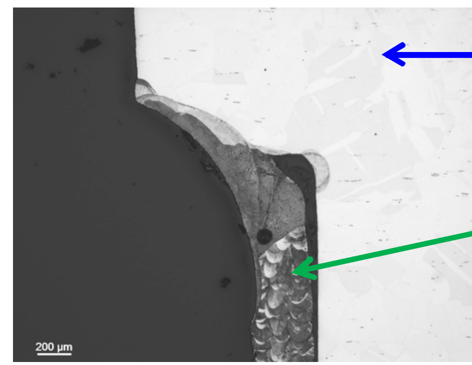
- Geometric freedom afforded by AM can reduce the need for welding in component designs; however, some designs will still require welding for final assembly
- Weldability considerations for metal AM components need to be addressed

General Electric LEAP Fuel Nozzle



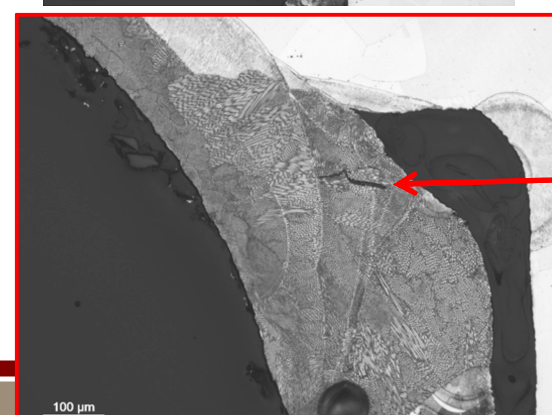
Fuel/air fittings and swirler require welding to AM mid-section

Example:
AM 304L Housing Laser Welded to 304L Connector



304L Connector

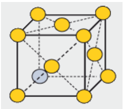
AM 304L Housing (no cracks in built part)



Weld solidification crack

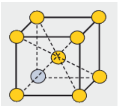
Alloy Chemistry is a Critical Variable in Determine Weld Solidification Crack Susceptibility

Primary Austenite

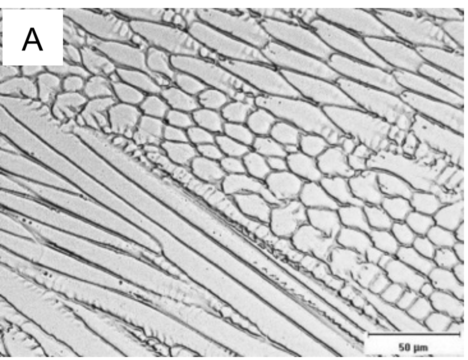


- <u>Increased solidification cracking concern</u>
  - Less tolerant of impurities (namely phosphorus + sulfur). Requires 'clean' alloys to preclude cracking.
  - Less tolerant of restraint

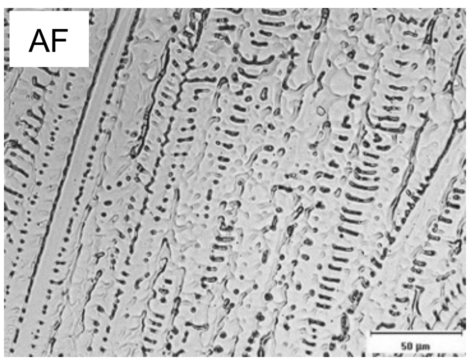
Primary Ferrite



- <u>Desired solidification mode</u>
  - Increased resistance to solidification cracking
  - More tolerant of restraint and impurity elements

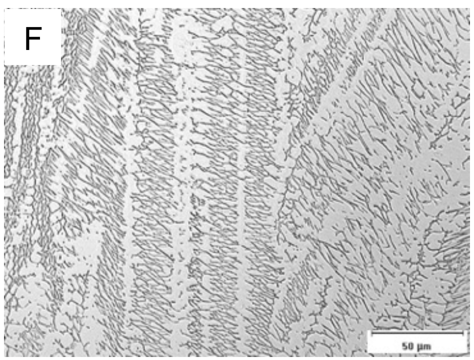


L → L + **A** → A



L → L + **A** → L + A + $(A+F)_{eu.}$ → A + $F_{eu.}$

L → L + **F** → L + F + $(A+F)_{eu./per.}$ → A + F



L → L + **F** → F → A + F

Austenite Promoters

<u>Ni</u>, C, N, Mn, Cu

Alloy Chemistry: Increasing $(Cr/Ni)_{eq}$ →

Ferrite Promoters

<u>Cr</u>, Mo, Si, Nb, Ti

Micrographs from: John C. Lippold, Damian J. Kotecki, <u>Welding metallurgy and weldability of stainless steels</u>, Wiley-Interscience, 2005, 357pgs

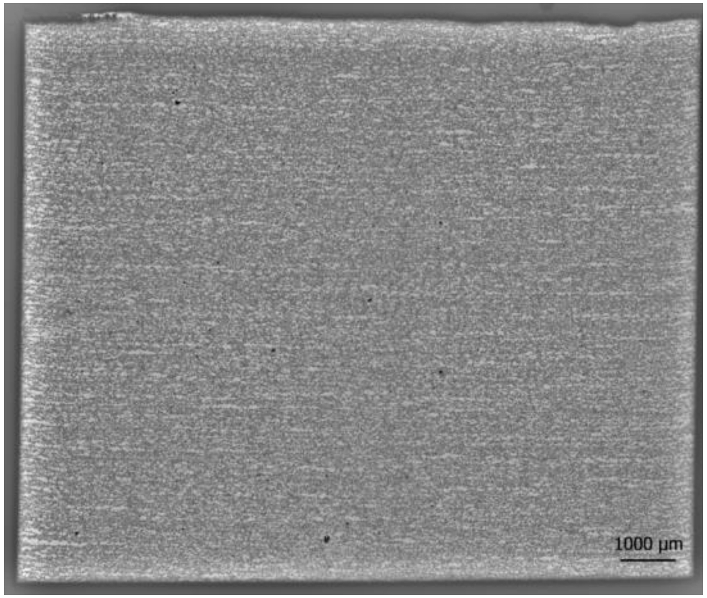
Microstructure of AM 304L Produced by Two Distinct Routes Examined

- Laser Powder Bed Fusion (PBF) and Laser Directed Energy Deposition (DED) examined
- Deposits made from a single heat lot of virgin powder
  - Resultant microstructures will be a function of solidification/thermal history

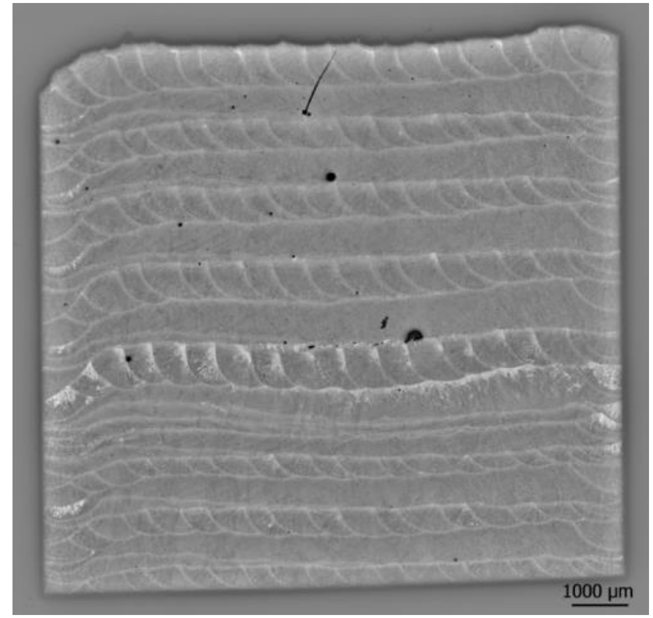
		Directed Energy Deposition		Powder Bed Fusion	
Sample	Mill Cert.	LANL1	LANL2	NSC R1-3	NSC R2-2
C	0.015	0.008	0.009	0.012	0.012
Cr	18.4	18.92	18.97	18.90	18.83
Co	NR	0.03	0.03	0.03	0.03
Nb	NR	0.03	0.04	0.04	0.03
Cu	NR	0.02	0.02	0.02	0.02
Mn	1.5	1.45	1.44	1.40	1.40
Mo	NR	0.01	0.01	0.01	0.01
Ni	9.8	9.93	9.93	9.92	9.92
N	0.05	0.044	0.043	0.049	0.044
O	0.019	0.022	0.019	0.040	0.035
P	0.012	0.009	0.009	0.009	0.009
Si	0.053	0.58	0.59	0.58	0.58
S	0.003	<.005	<.005	<.005	<.005
V	0.01	0.02	0.02	0.02	0.02

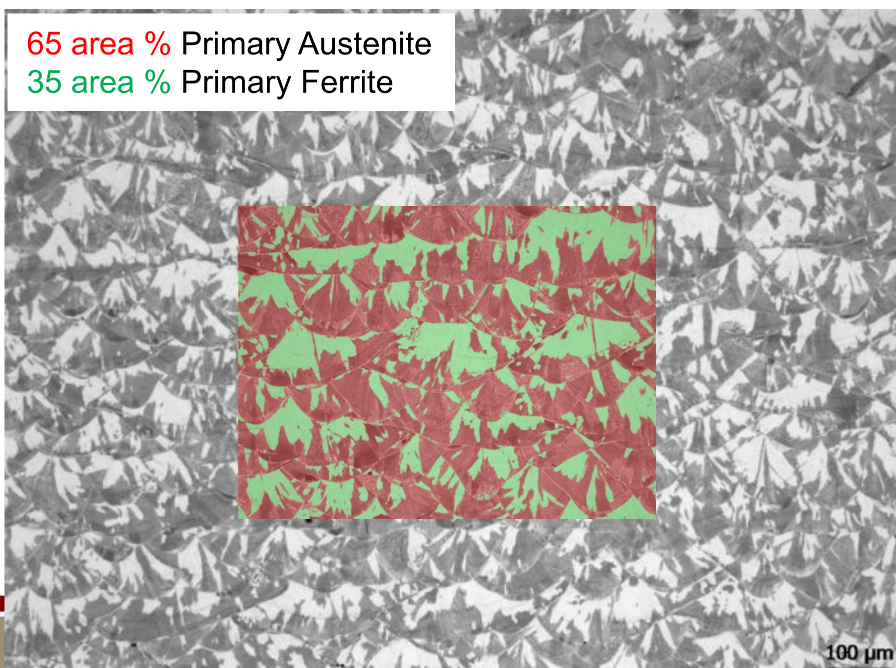
Powder Bed Fusion (PBF)

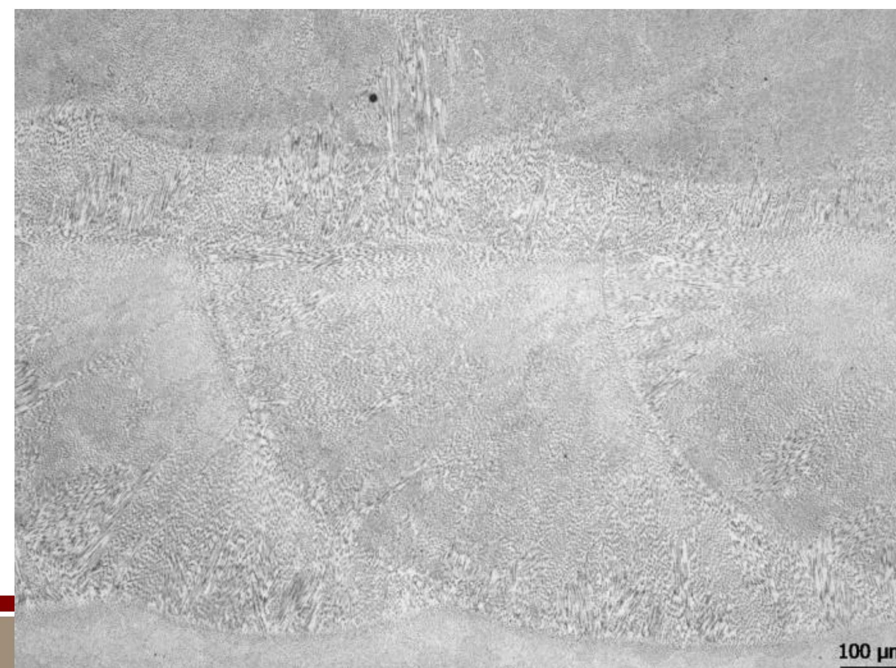
Directed Energy Deposition (DED)



Build Direction

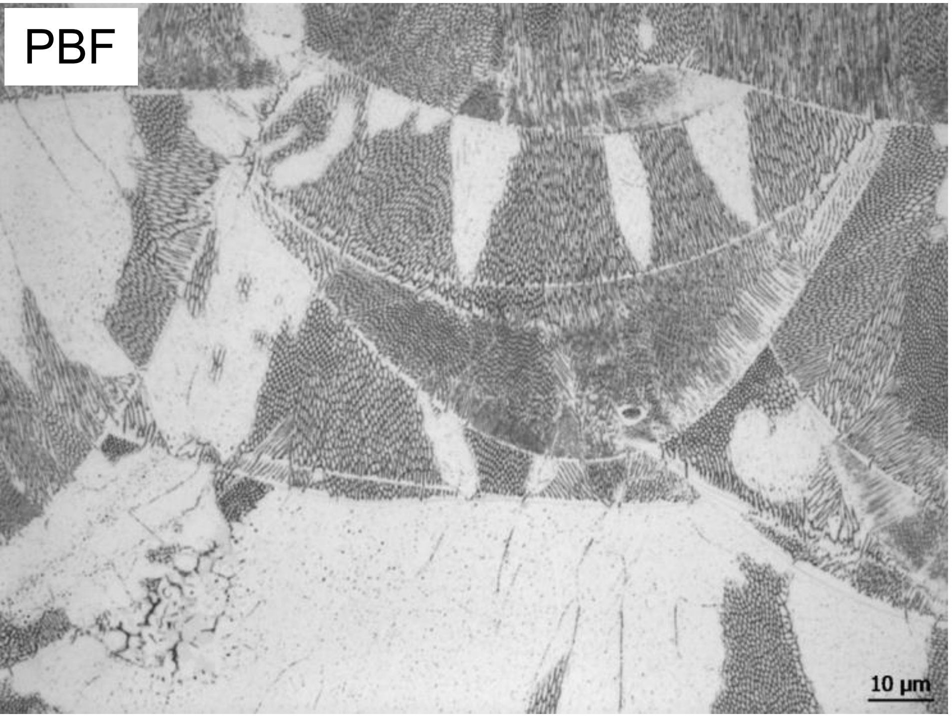


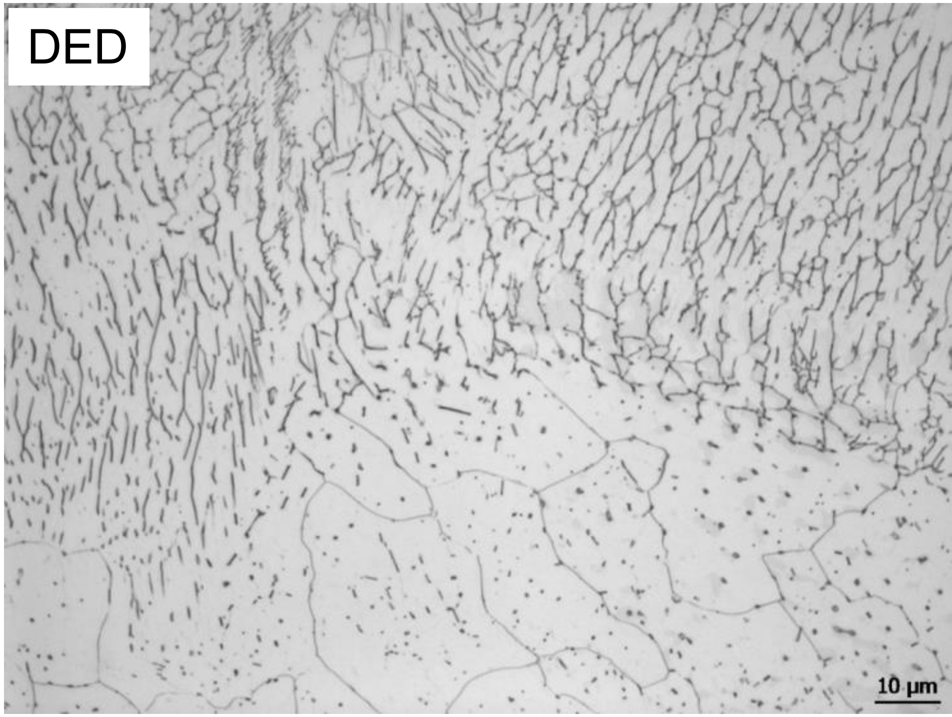




High-magnification light optical micrographs

- PBF build shows mixed mode solidification with large fraction primary austenite
- DED microstructure characteristic of primary ferrite (Type FA)

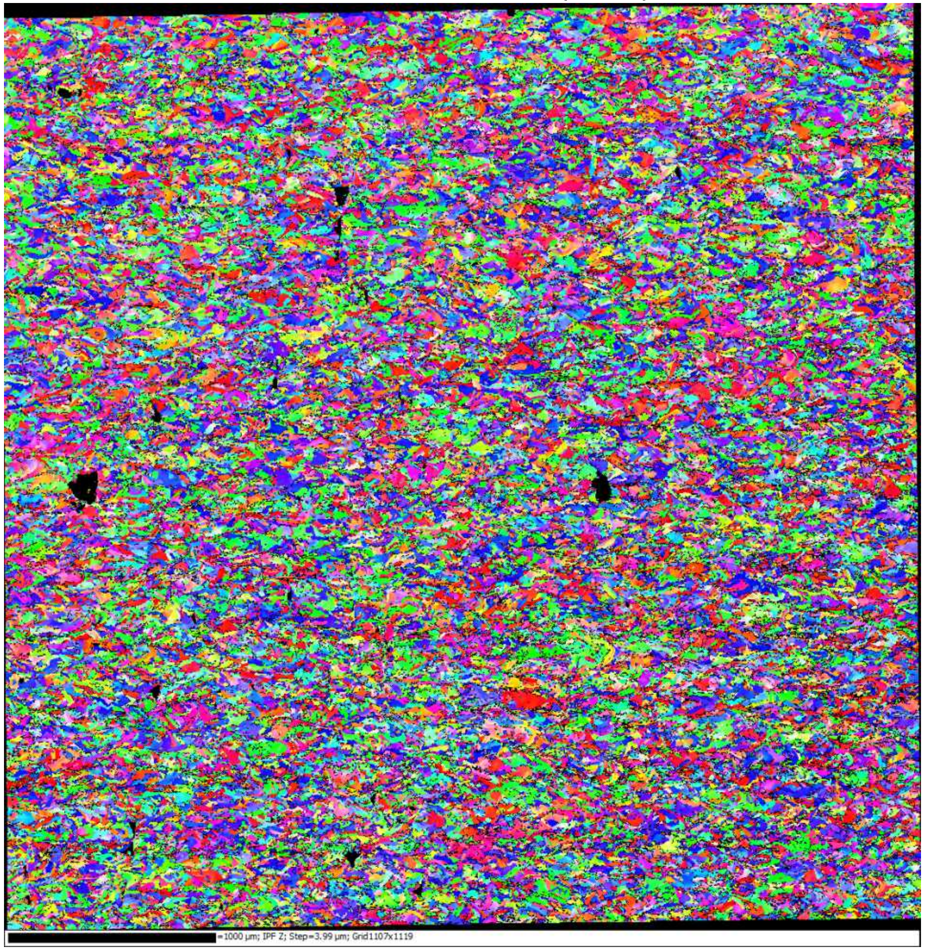




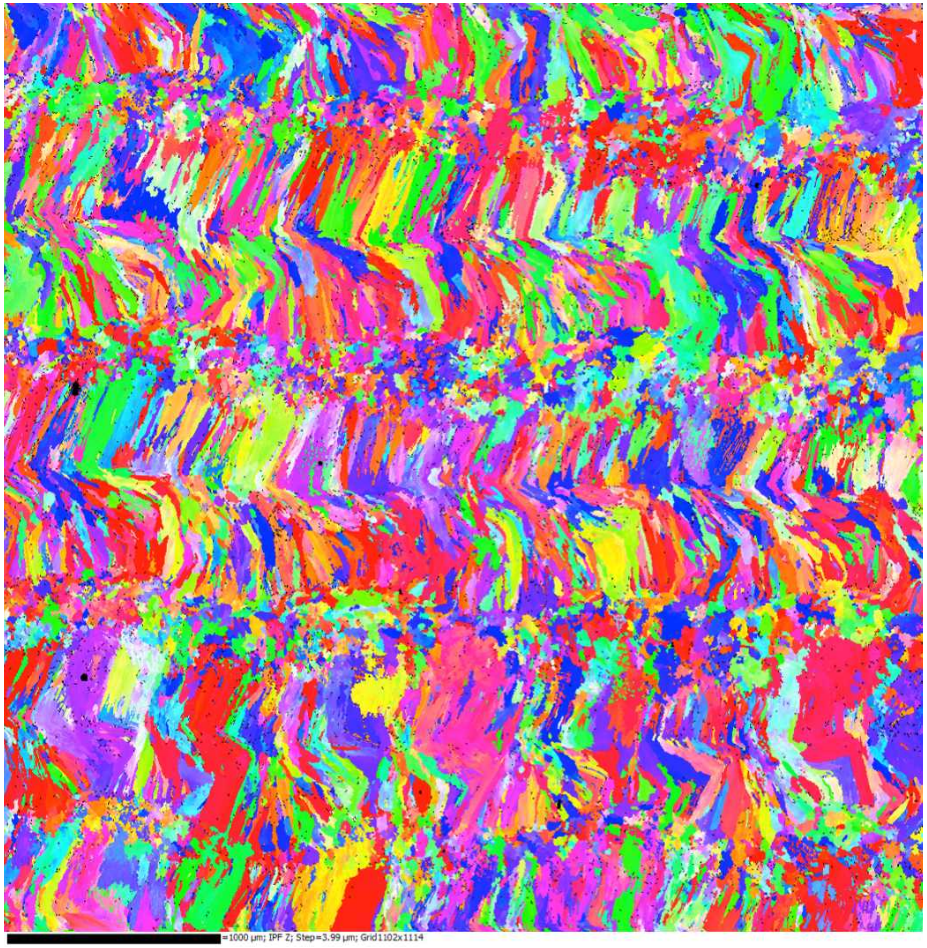
Stage Scan EBSD

Build Direction

Powder Bed Fusion (PBF)



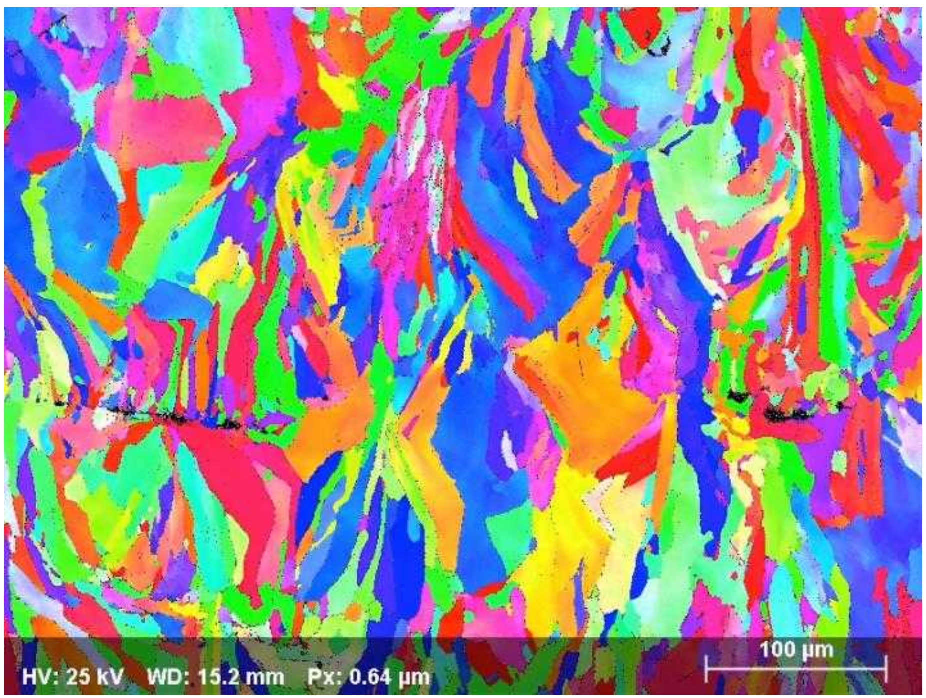
Directed Energy Deposition (DED)



AM 304L: EBSD

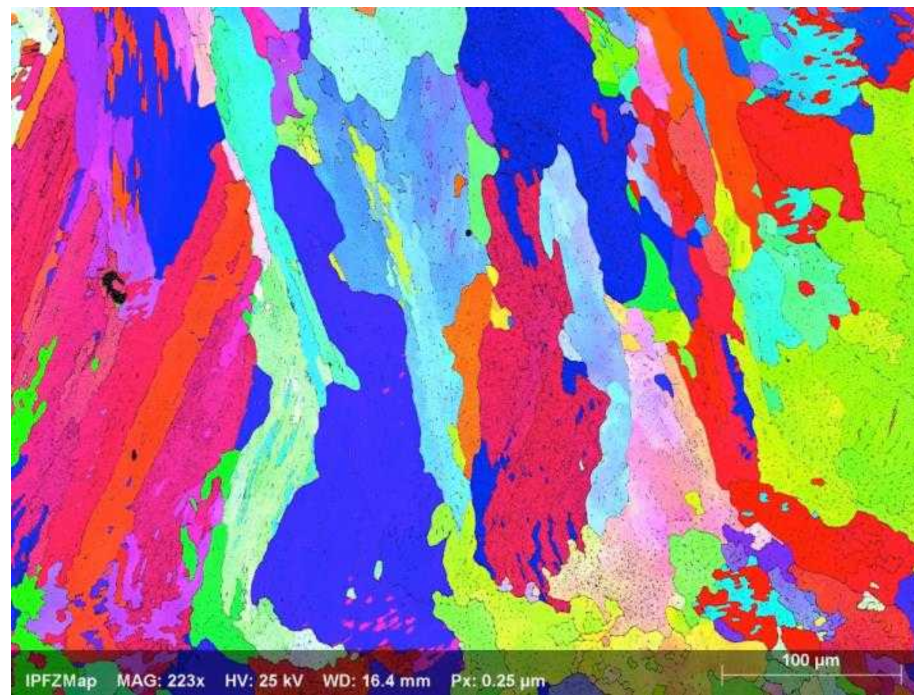
- PBF results in finer high-angle solidification grains compared to DED
- DED contains fine dispersion of residual delta-ferrite

<u>Powder Bed Fusion (PBF)</u>

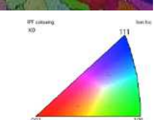


<u>0-0.1 vol.% ferrite</u>

<u>Directed Energy Deposition (DED)</u>



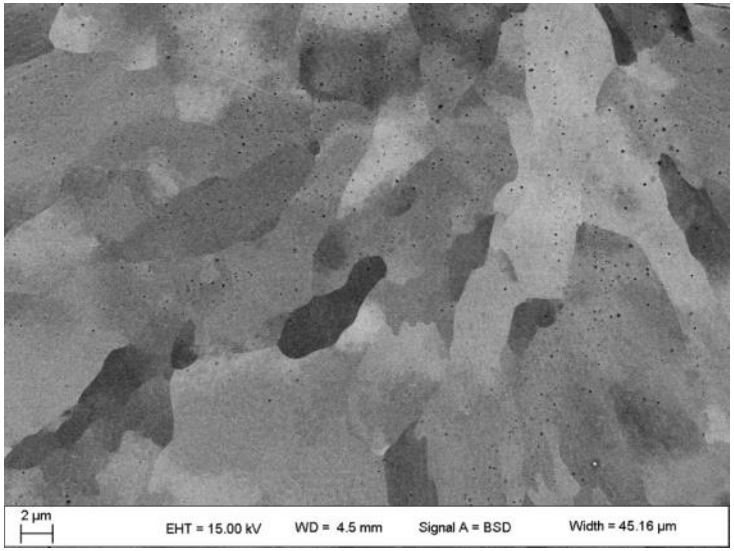
<u>1.9-2.3 vol.% ferrite</u>

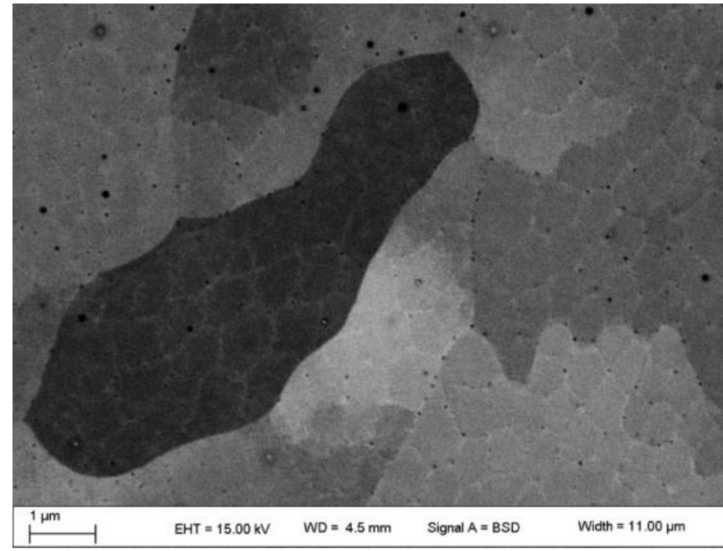


Solidification Process for PBF vs. DED Results in Solidification Mode Shift

- Large cooling rate difference between DED and PBF results in mode shift!
- <u>Difference in resultant microstructure has property implications</u>

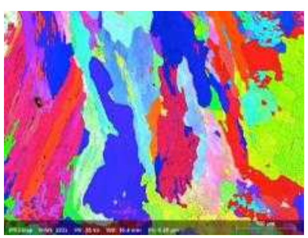
PBF

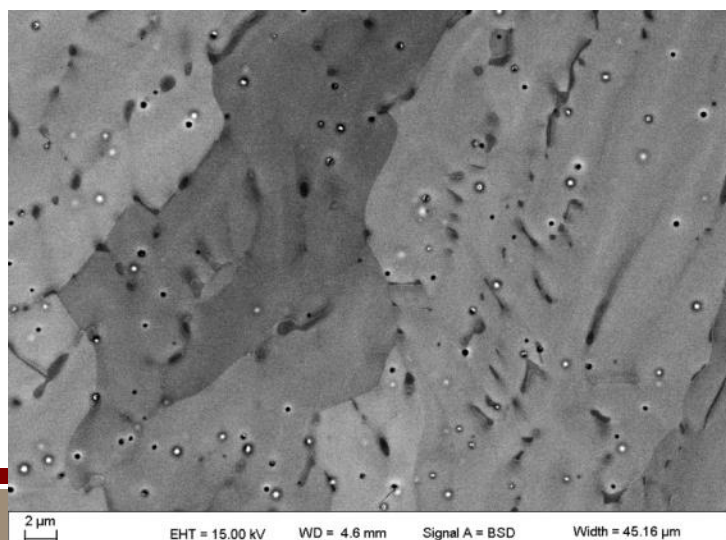




L → L + **A** → <u>A</u>

DED

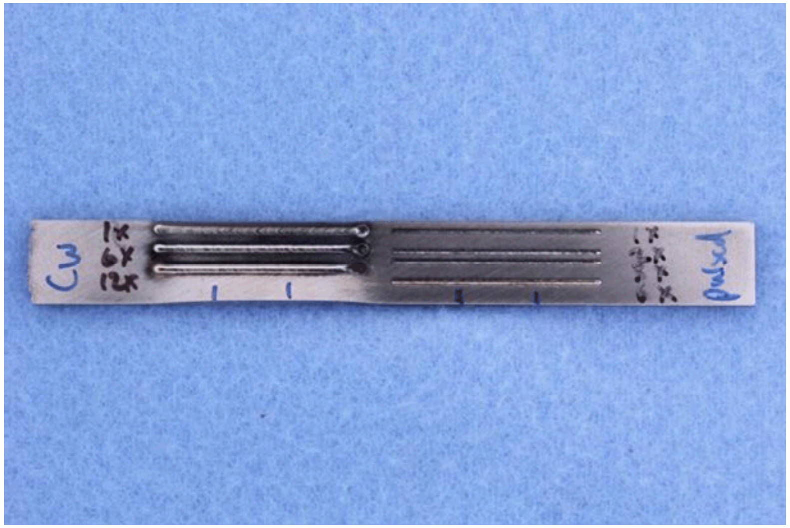




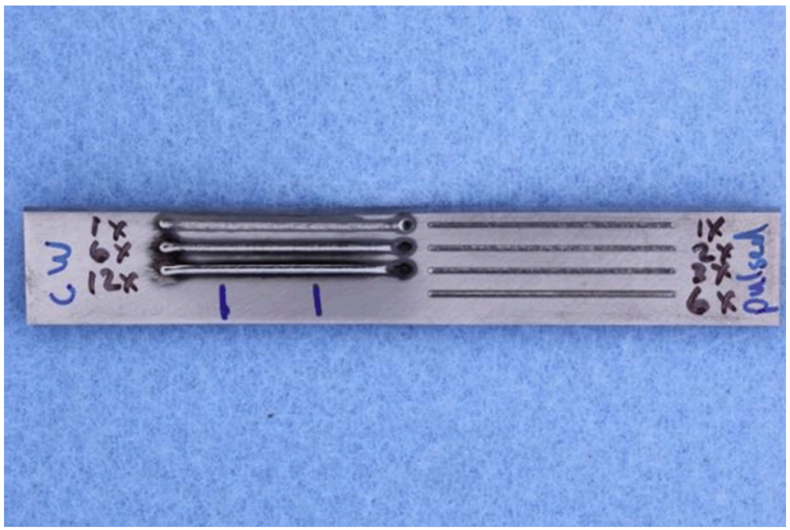
L → L + **F** → L + F + $(A + F)_{eu./per.}$ → <u>A + F</u>

AM 304L Autogenous Laser Welding Trials

DED



PBF



Two Laser Welding Procedures Explored:

- Pulsed: 2.7 J/pulse @ 5 Hz; 1.5 ipm, ~525 W peak power, ~14 W avg.; 100 CFH co-axial Ar shielding
- CW 425 W, 80 IPM travel speed, 100 CFH co-axial Ar shielding
- Bead-on-plate seam welds

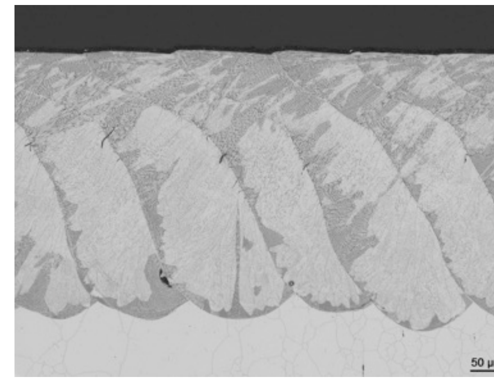
Why investigate the multiple melting and solidification behavior for welds?

- We often receive inquiries into rewelding limits for component reuse featuring autogenous laser welds
  - Technical basis for limits are not well-established

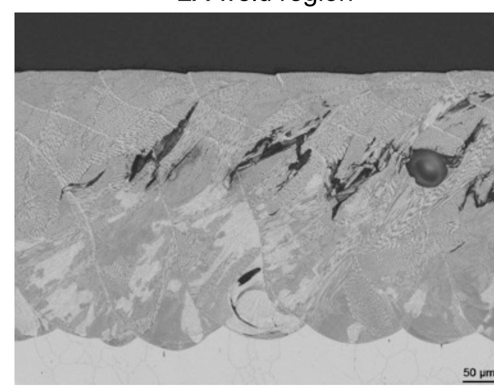
Practical Example

- A prototype enclosure assembly was to be joined using laser welding
- Housing and cover made from commercial vacuum arc remelted 304L (Low P+S, $(Cr/Ni)_{eq}$ = 1.73)
- The small size and thermal constraints for this housing required laser pulsed seam welding
- <u>Visual inspection of weld revealed hot cracks in weld termination overlap region</u>

1X weld region



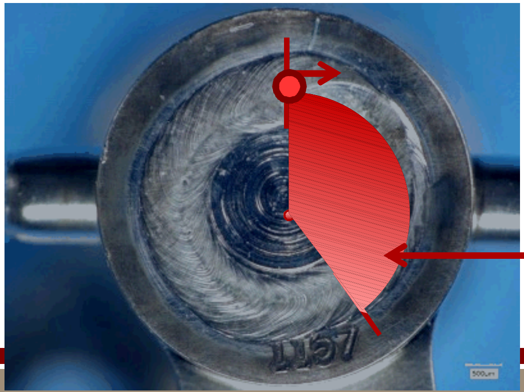
2X weld region



Multiple Melting/Solidification Events in Laser Welds Are Commonly Encountered in Practice

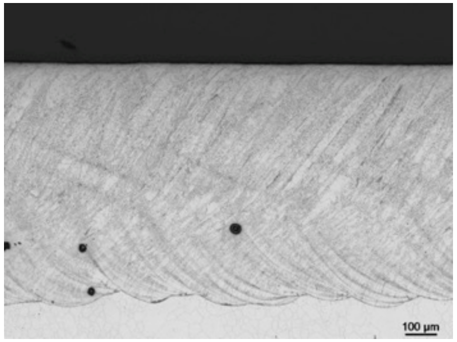
- Autogenous laser welding can impose a surprisingly high number of melting/solidification cycles on a given volume in a weld joint

- Closure welds have an overwelded termination
- Most welding specifications allow repair/rework welding
- Surveillance and reuse concepts can impose additional cycles
- Pulsed seam welding adds additional melting/solidification cycles compared to continuous wave
- Each cycle provides an opportunity for composition changes due to evaporation or impurity uptake

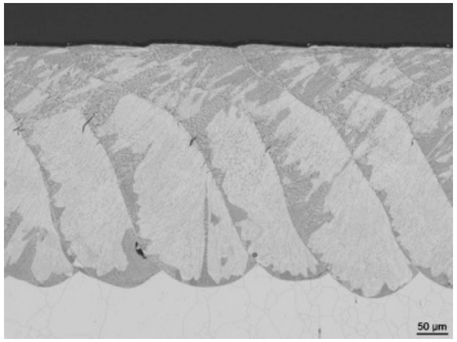


Example laser weld path

CW Seam



Pulsed Seam



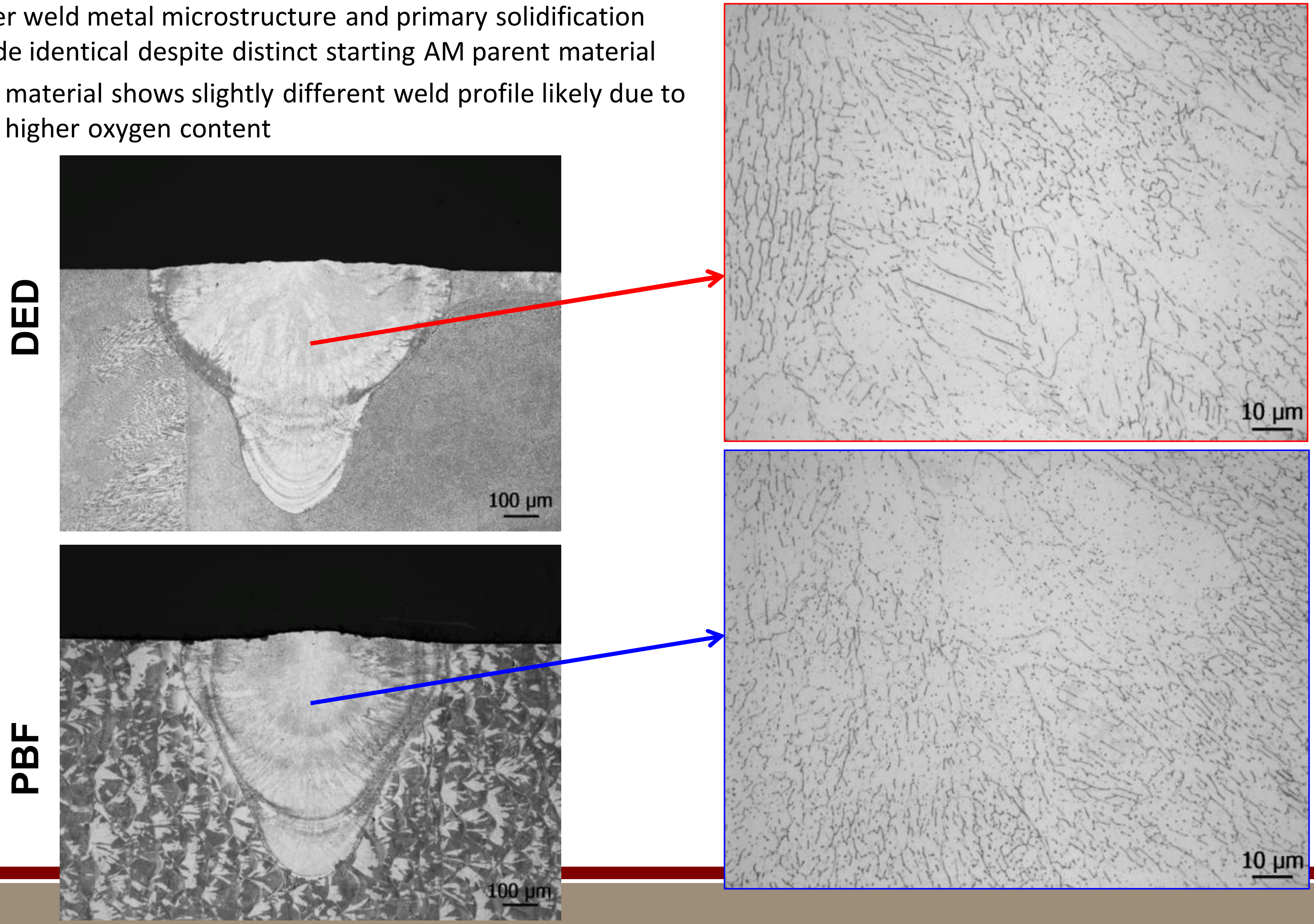
Weld Termination Region

$(2_{\text{termination overlap}})(3_{\text{rework/reweld}})(2_{\text{reuse}})$ = 12 cycles

$(3_{\text{pulse overlap}})(2_{\text{termination overlap}})(3_{\text{rework/reweld}})(2_{\text{reuse}})$ = 36 cycles

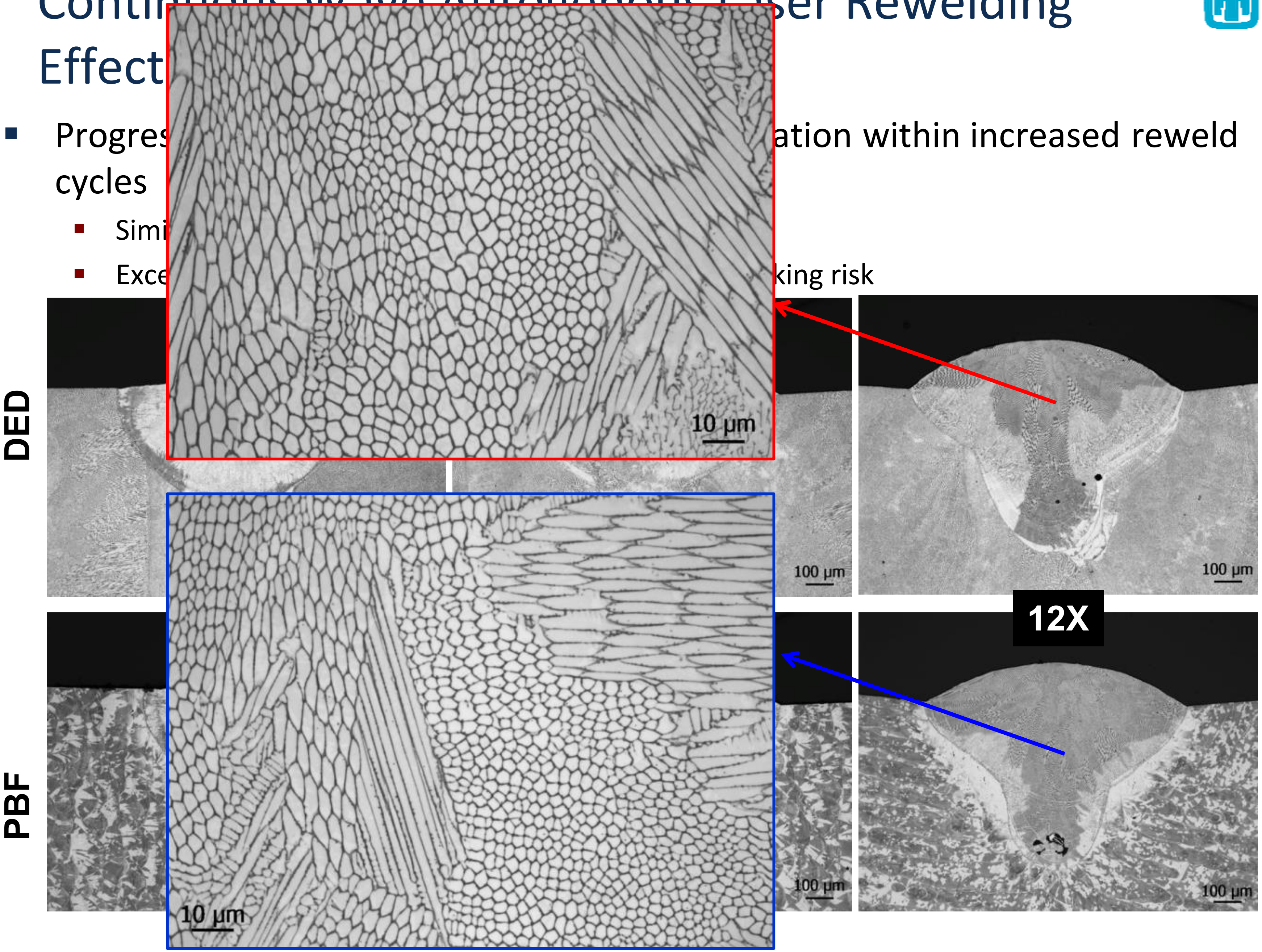
Continuous Wave Autogenous Laser Welding Trials

- Laser weld metal microstructure and primary solidification mode identical despite distinct starting AM parent material
- PBF material shows slightly different weld profile likely due to ~2X higher oxygen content



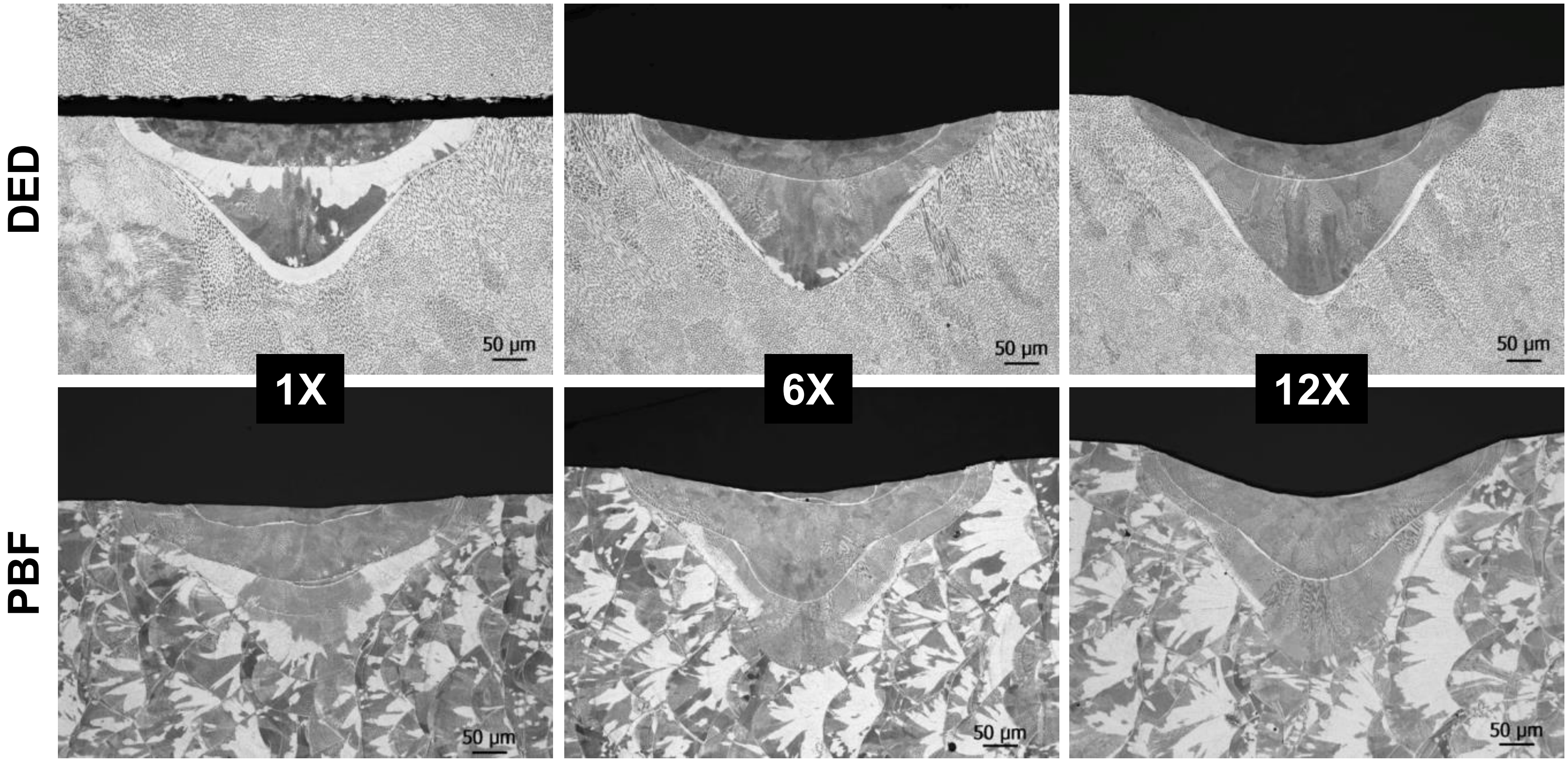
Contin... Wave Autogenous Laser Rewelding Effect...

- Progres... ation within increased reweld cycles
  - Simi...
  - Exce... king risk



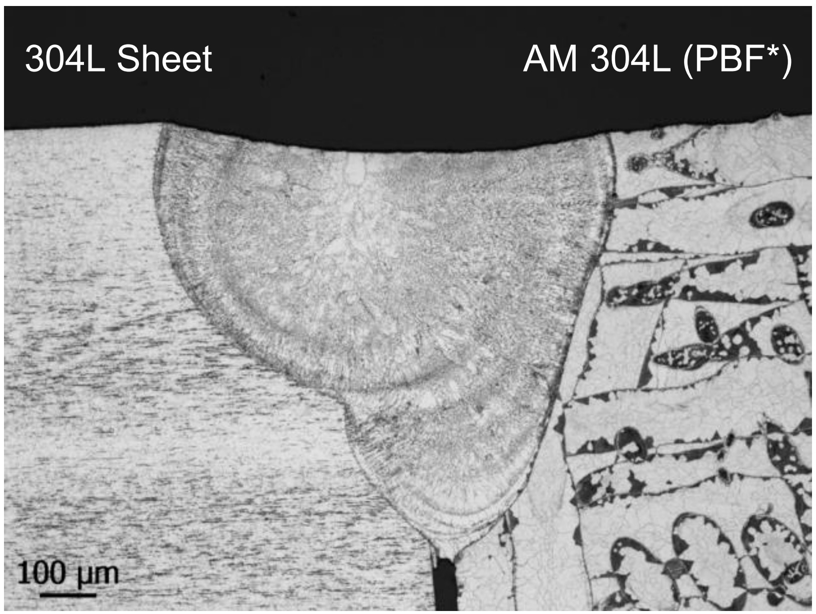
Pulsed Seam Autogenous Laser Rewelding Effects

- Progressive shift in solidification mode from mixed mode to fully primary austenite with increasing reweld number



Increased Oxygen Content of PBF AM 304L Can Result in Asymmetric Dissimilar Weld Profiles

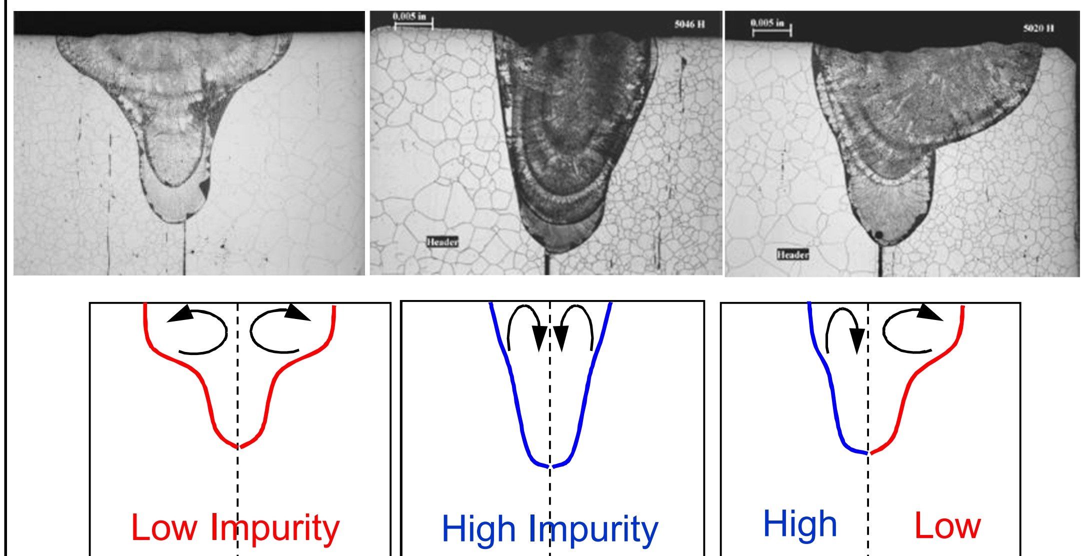
- Bulk oxygen concentration of PBF AM 304L can be substantially higher than typical conventional 304L levels
- Past SNL investigations have observed similar weld profile asymmetry when laser welding 304L components with varying levels of surface oxide
- Asymmetry not intrinsically deleterious, but can pose post weld inspection challenges for some applications



0.003 wt.% O
0.001 wt.% S

0.036 wt.% O
0.005 wt.% S

Effect of surface-active impurity elements on LBW workpiece surfaces



AM Bulk Composition is Critical Factor in Determining Weldability

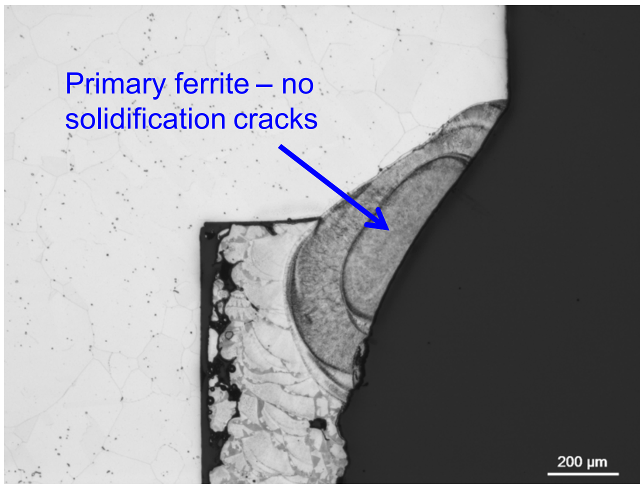
- Laser weld metal microstructure dictated by weld process parameters and starting bulk chemistry.
  - Results show no observed dependency on starting AM 304L solidification microstructure

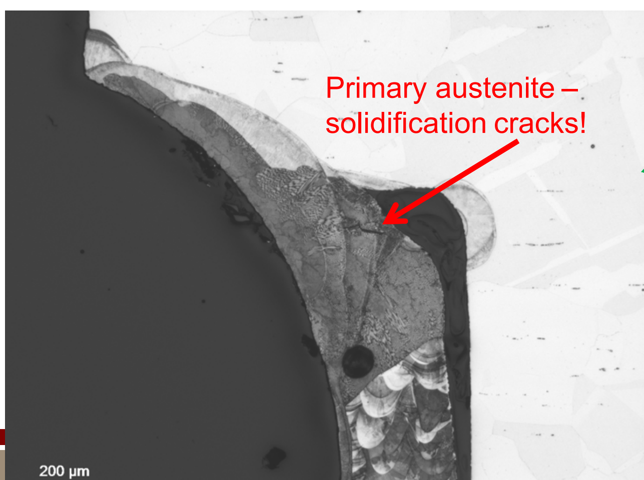
- A shift in operative primary solidification mode was observed for different fusion AM 304L processes based on large difference in cooling rate

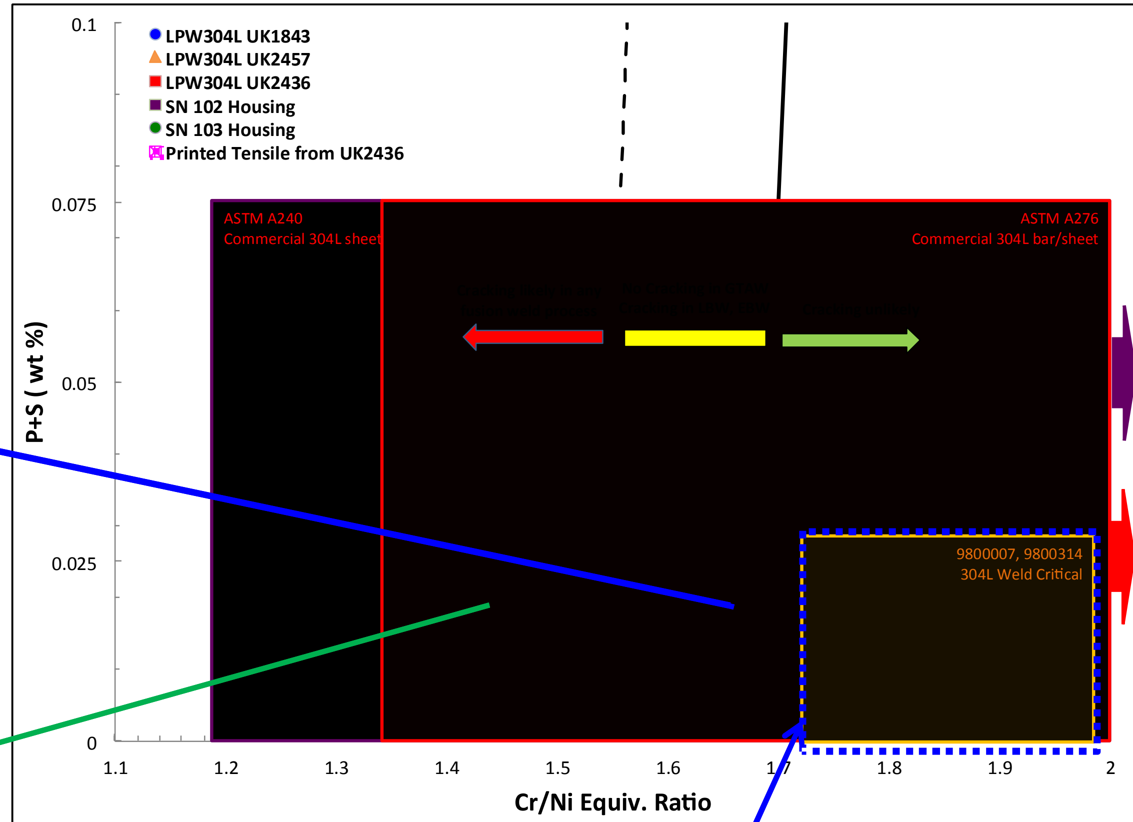
- Marangoni-flow changes due to differences in surface-active elements can lead to weld profile shape change

Stringent Control of Starting AM Powder Chemistry Is Required to Ensure Weldability

- Powder chemistries amenable to laser welding (high $(Cr/Ni)_{eq}$ and low impurity) require the development of tighter allowable composition ranges to prevent solidification crack susceptible microstructure







'Weld-Critical' AM 304L powder range

18

Future Work

- Quantitative weldability studies on AM 304L including Gleeble hot ductility and Varestraint testing
- Examination of porosity distribution for laser welds produced on AM 304L
- Continue development efforts with AM metal powder producers to further refine composition space for ‘weld-critical’ powder chemistries

Acknowledgments

- SNL
  - Alice Kilgo
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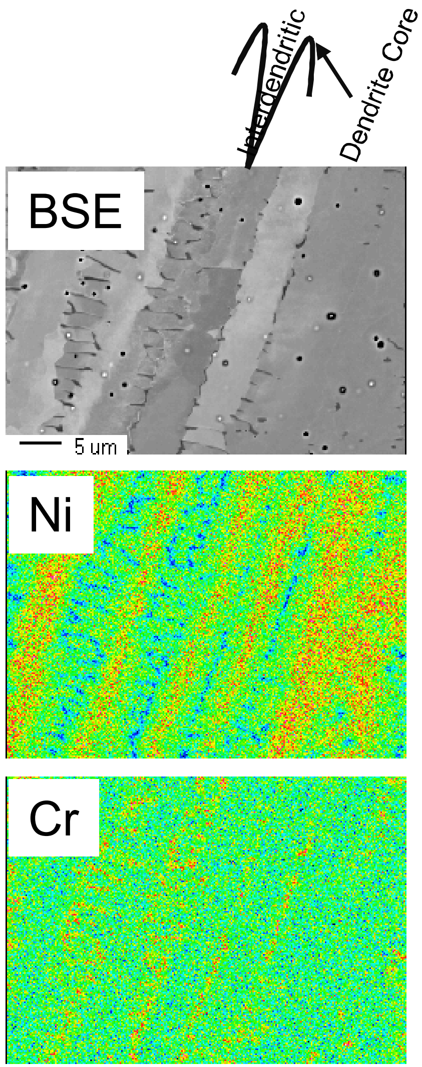
- KCNSC
  - Andrew Vance
  - Ben Brown
  - Brett Griffith

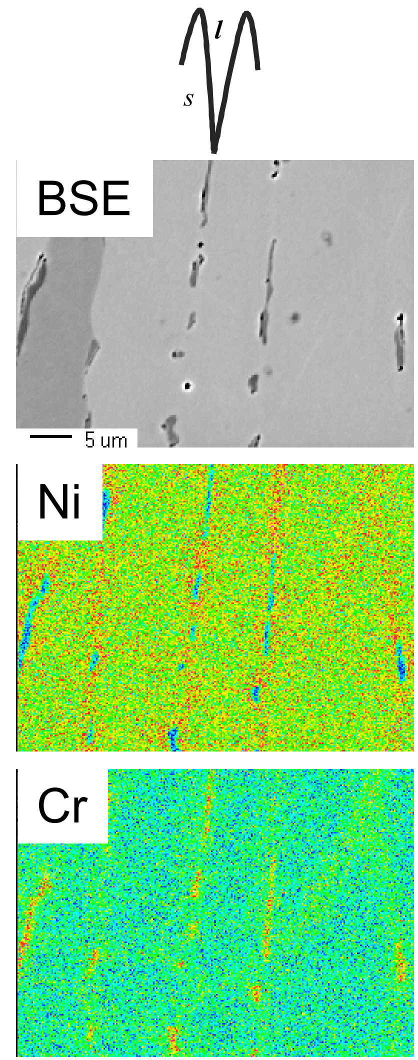
Backup Slides

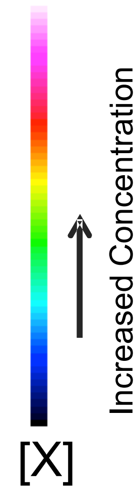
Example: WDS Determination of Primary Solidification Mode

Primary **Ferrite** Solidification
(LENS 304L 3.8 kW)
Type FA: L → L+F → L + F $(F+A)_{eu.\text{-}per.}$ → A +F



Primary **Austenite** Solidification
(310S Cast Pin [GTAW-like cooling rates])
Type AF: L → L+A → L + A $(F+A)_{eu.}$ → A + $F_{eu.}$





$k_{Cr} > 1$; $k_{Ni} < 1$

k_{Cr} & $k_{Ni} < 1$

WDS Microprobe Confirms Primary Solidification Mode Assessment

- DED 304L shows Ni max. corresponding to Cr min. within interdendritic region corresponding to primary ferrite solidification segregation profile
- PBF 304L solidification substructure beyond resolution of WDS microprobe