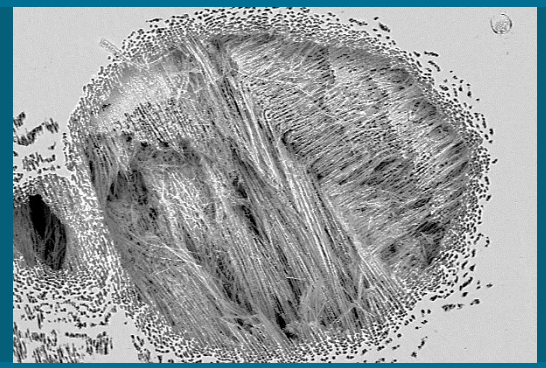
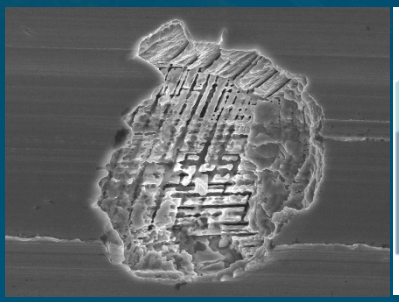
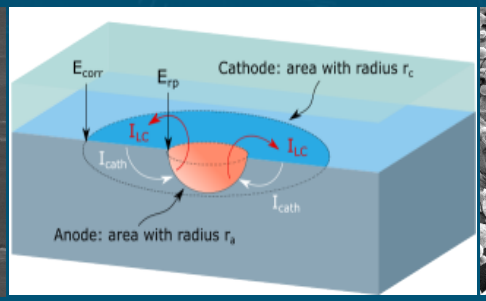
SAND2022-2091C

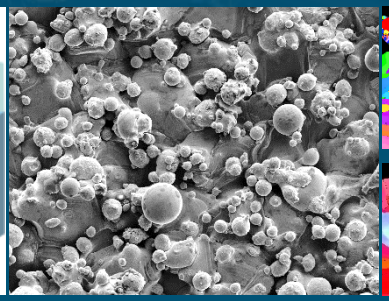
Sandia National Laboratories

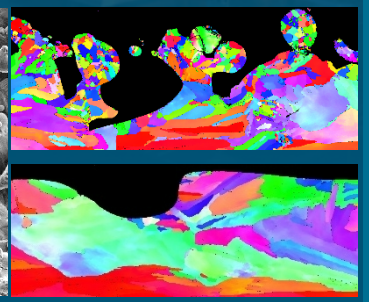
# How part surfaces influence corrosion for a laser powder bed fusion 316L stainless steel










**TMS 2022**
**February 27–March 3, 2022**
**Anaheim, California, USA**

PRESENTED BY

Michael Melia

Contributors: Erin Karasz, Kasandra Escarcega-Herrera, Jay Taylor, Samantha Rosenberg, Paul Kotula, Michael J. Heiden, Jeffrey M. Rodelas

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

SAND# XXXX-XXXX

# Process flow map for metal AM component

**Component design/optimization**

- Topology optimization
- Improve functionality/product reliability
- Reduced cost/material waste

**Material choice/development**

- Improved properties
- Reduce constraints

**Process**

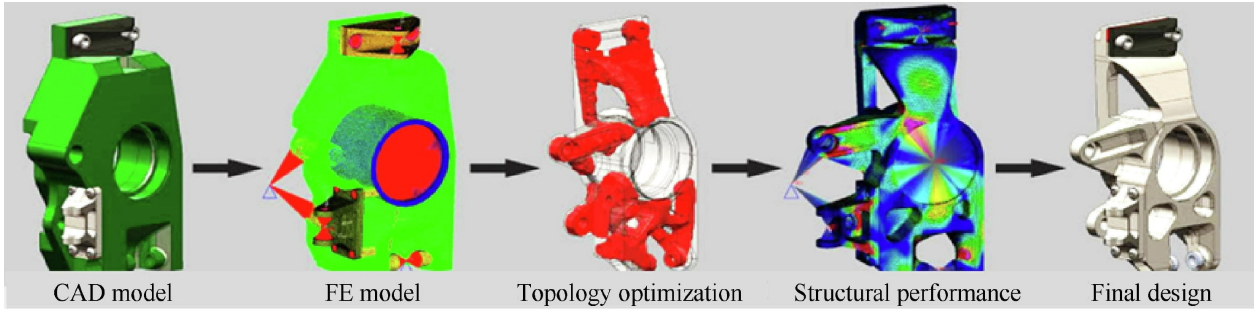
- Select manufacturing technique
- Process optimization
- Print components

**Post processing**

- Remove components from build plate
- Stress relief
- Machining/surface finishing

**Quality assurance**

- Specification and standards testing & failure analysis
- Reduced risk




J. Zhu, et al., Chinese Journal of Aeronautics, (2021).

| Material Classification | UNS/Similar product |
|---|---|
| Stainless steel | S15500/15-5PH |
| | S17400/17-4PH |
| | S30403/304L |
| | S31603/316L |
| Ni-based Superalloy | N06625/Ni alloy 625 |
| Ni-Fe Superalloy | N07718/Ni alloy 718 |
| Co-based Superalloy | R31537/CoCr |
| High Performance Titanium | R56400/Ti6Al4V |
| Aluminum Alloy | AlSi10Mg |

Adapted from Carpenter website

# Process flow map for metal AM component

**Component design/optimization**

- Topology optimization
- Improve functionality/product reliability
- Reduced cost/material waste

**Material choice/development**

- Improved properties
- Reduce constraints

**Process**

- Select manufacturing technique
- Process optimization
- Print components

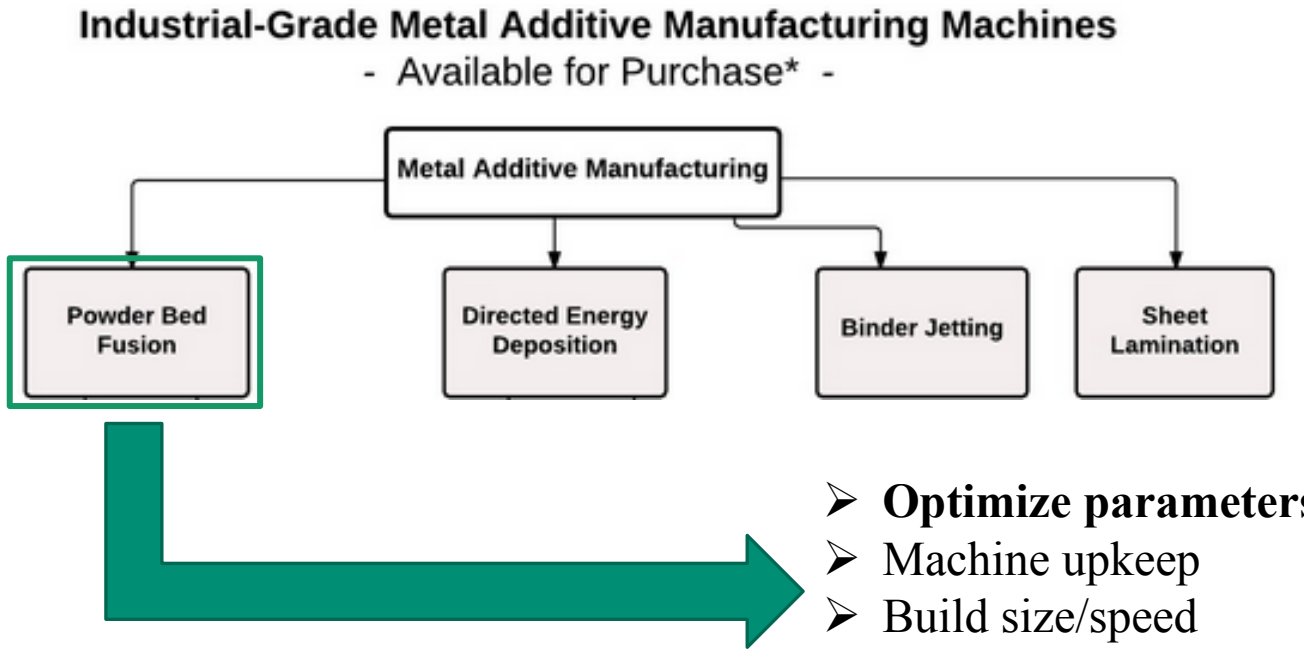
**Post processing**

- Remove components from build plate
- Stress relief
- Machining/surface finishing

**Quality assurance**

- Specification and standards testing & failure analysis
- Reduced risk

(UUR)




- **Optimize parameters**
- Machine upkeep
- Build size/speed
- # of parts per build

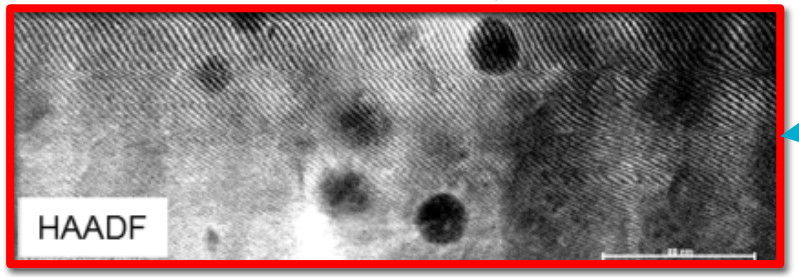
From Sciaky website (https://www.sciaky.com/metal-additive-manufacturing-methods)

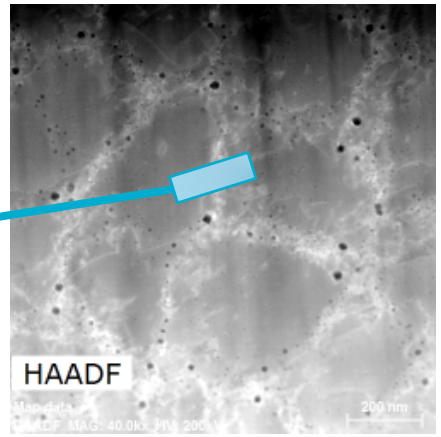
# Microstructural features from powder metal AM

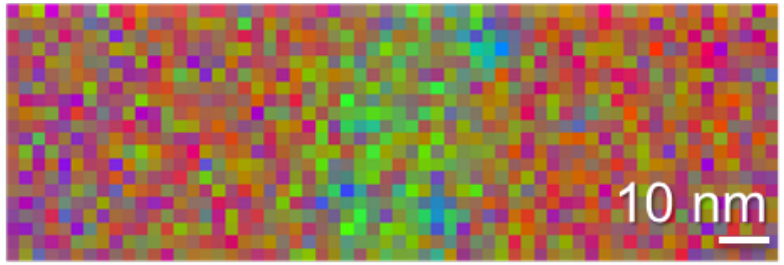
## Chemical heterogeneities

**Cell walls decorated with oxides**

Matrix Cell Boundary Matrix

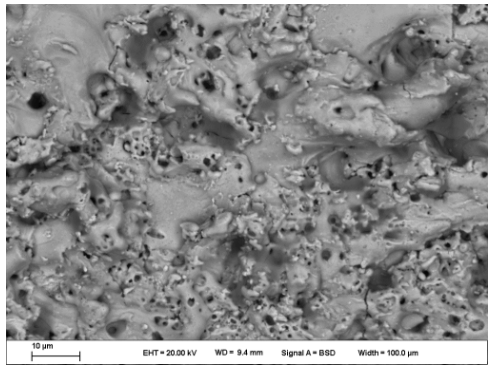


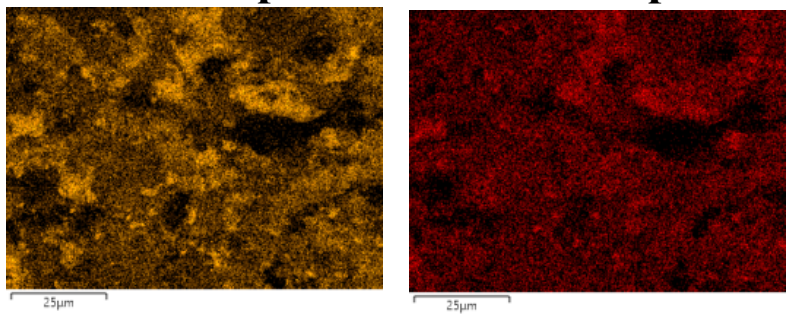




Adapted from Schaller, 2018

## Recast layer from a part removed with wire EDM



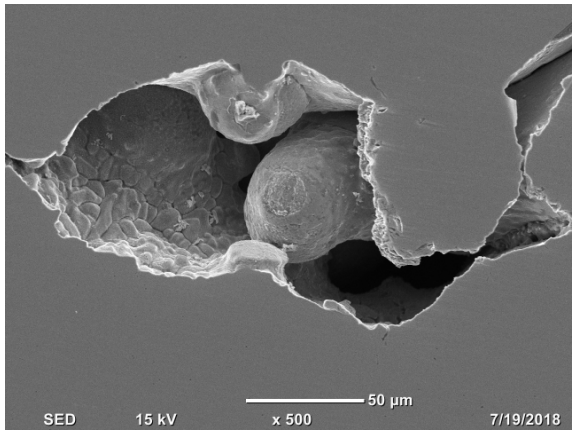
**Cu map** **Zn map**



Cu and Zn penetrate 5 to 10 µm deep.

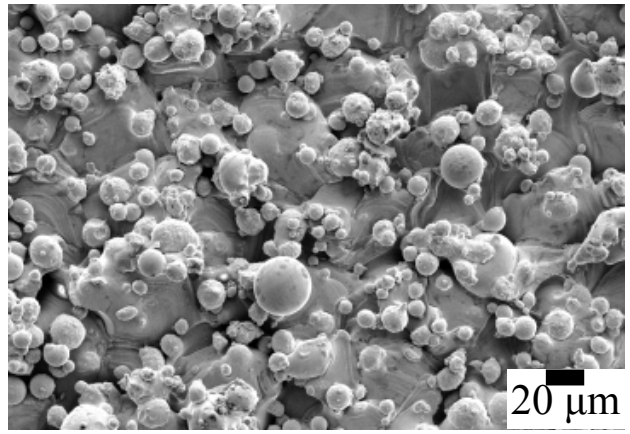
## Processing defects

**Porosity**




Melia, 2019

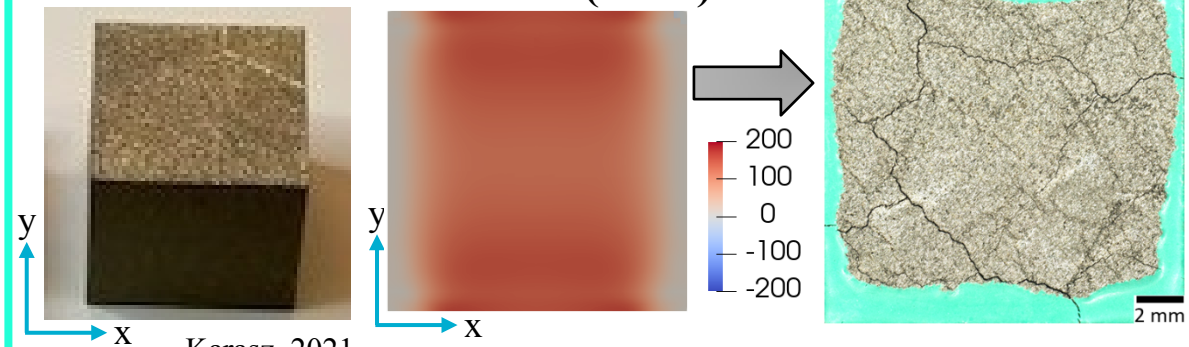
**Surface roughness**




Melia, 2020

## Residual stress of 316L cubes

**Stress XX (MPa)**




Karasz, 2021

Leads to susceptibility to stress corrosion cracking

(UUR)

# Process flow map for metal AM component

**Component design/optimization**

- Topology optimization
- Improve functionality/product reliability
- Reduced cost/material waste

**Material choice/development**

- Improved properties
- Reduce constraints

**Process**

- Select manufacturing technique
- Process optimization
- Print components

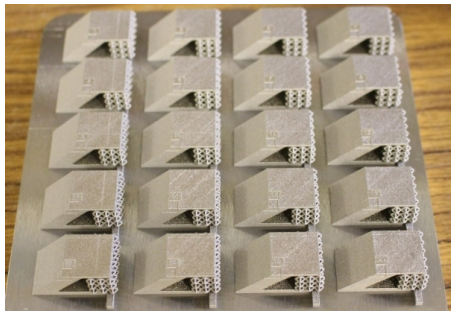
**Post processing**

- Remove components from build plate
- Stress relief
- Machining/surface finishing

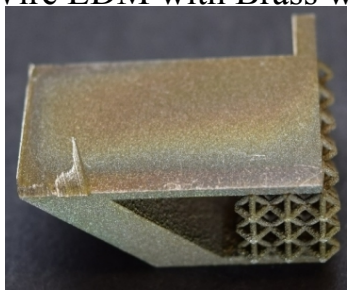
**Quality assurance**

- Specification and standards testing & failure analysis
- Reduced risk

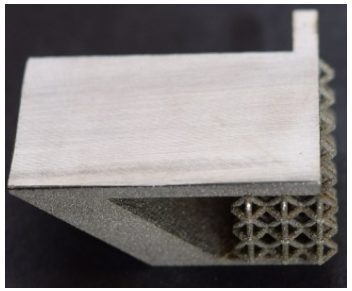
## Remove from build plate



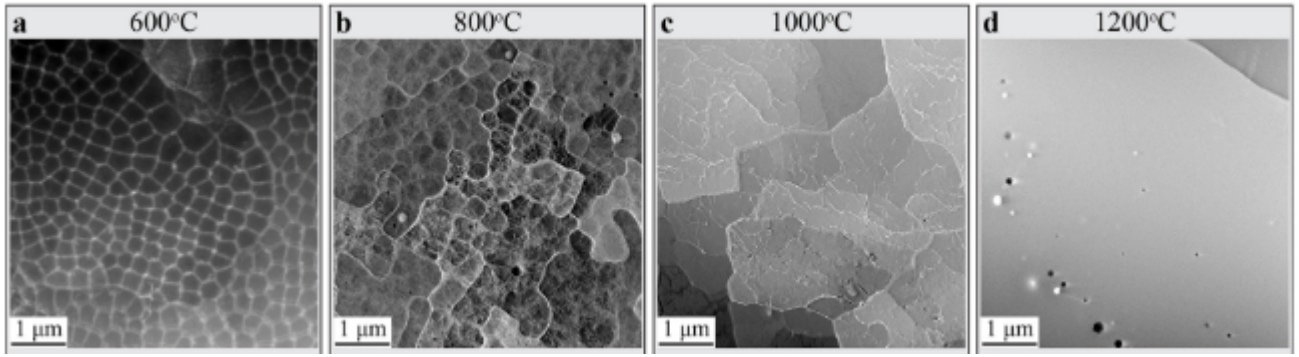
Wire EDM with Brass wire



Bandsaw cut

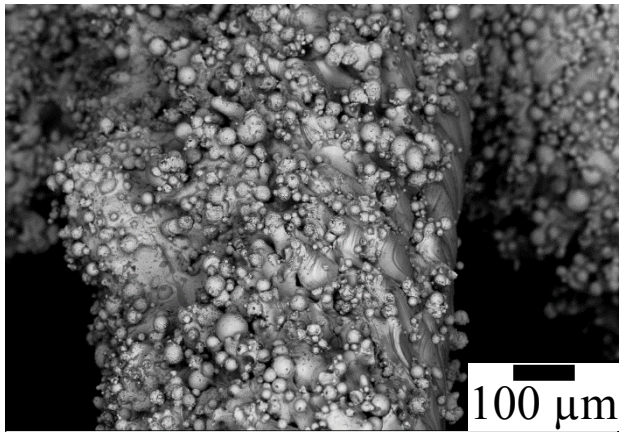


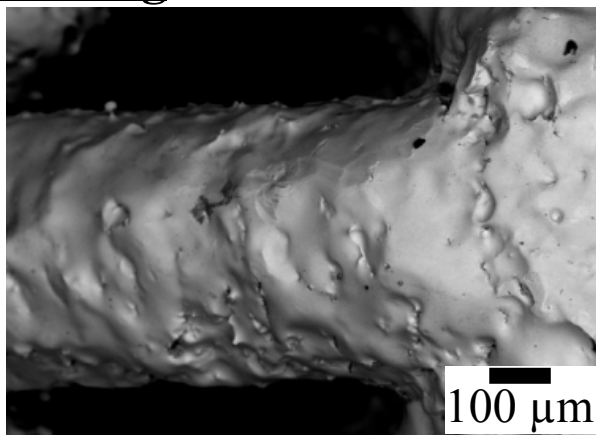
## Heat treatments




T. Voisin et al. Acta Materialia (2021)

## Surface finishing




(UUR)

# Process flow map for metal AM component

**Component design/optimization**

- Topology optimization
- Improve functionality/product reliability
- Reduced cost/material waste

**Material choice/development**

- Improved properties
- Reduce constraints

**Process**

- Select manufacturing technique
- Process optimization
- Print components

**Post processing**

- Remove components from build plate
- Stress relief
- Machining/surface finishing

**Quality assurance**

- Specification and standards testing & failure analysis
- Reduced risk

(UUR)

October 15, 2021

https://www.metal-am.com/**wohlers**-releases-report-on-post-processing-of-am-parts/

Many could benefit from using AM metals in their as-printed state:

- Reduces costs
- Reduces lead times
- ***Possibly beneficial effects??***

*However, there are cases were if you cant remove the as-printed surface, then the AM risk case is elevated to high risk (per NASA-STD-6030), and it is recommended to machine all surfaces.*

# What will we go over in this talk?

- In-depth characterization of **as-printed** surfaces (LB-PBF 316L).
- Explore corrosion behavior of **as-printed** 316L parts when exposed to the accelerated corrosion test, ASTM G85-A2.

# Acknowledgements

**Funding:** The ACT program, DOD-DOE Joint Munitions Program (JMP), Aging and Lifetime Program.

**Many people to thank…**

**SNL:** Kasandra Escarcega-Herrera, Erin Karasz, Jesse Duran, Jason M. Taylor, Rebecca F. Schaller, Jeffrey M. Rodelas, Michael J. Heiden, Bradley H. Jared, Eric J. Schindelholz, Joseph Michael, Paul Kotula, Philip Noell, Daniel Perry, David Saiz, Mark Wilson, Brendan Nation, Joshua Koepke, Christina Profazi, Sara Dickens, Luis Jauregui, Alex Hickman

**UVA:** Rebecca S. Marshall, Danyil Kovalov, Ryan Katona, Ji Ma, Robert Kelly

**LANL:** Courtney Clark, Tim Gorey, Jamie Stull, Colt Montgomery, Daniel Hooks

**KCNSC:** Lucas Rice, Jonathan Dwyer, Andy Deal, Zach Rueger, Francisco Garcia-Moreno

**SRNL:** Patrick Kuzbary, Savidra Lucatero, Prabhu Ganesan, Hector Colon-Mercado, Paul Korinko

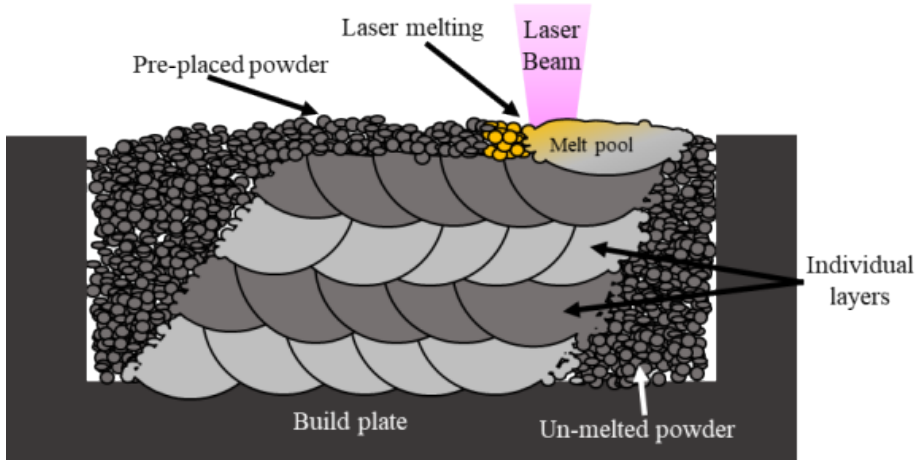
**LLNL:** Margaret Wu, Seongkoo Cho, Monika M. Biener, Y. Morris Wang, Justin Jones, and S. Roger Qiu, …

***Thanks to the symposium organizers for this opportunity.***

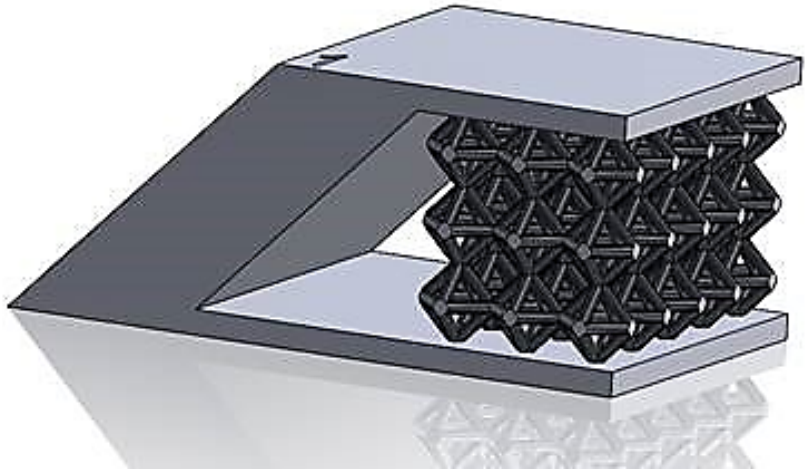
Publications on topic:

E.J. Schindelholz, et al., Corrosion of Additively Manufactured Stainless Steels—Process, Structure, Performance: A Review, Corrosion, 77 (2021).
M.A. Melia, et al., Marine Atmospheric Corrosion of Additively Manufactured Stainless Steels, Corrosion, (2021).
M.A. Melia, et al., How build angle and post-processing impact roughness and corrosion of additively manufactured 316L stainless steel, npj Materials Degradation, 4 (2020).
M.A. Melia, et al., Corrosion properties of 304L stainless steel made by directed energy deposition additive manufacturing, Corros. Sci., (2019).
R.F. Schaller, et al., The Role of Microstructure and Surface Finish on the Corrosion of Selective Laser Melted 304L, J. Electrochem. Soc., 165 (2018).
R.F. Schaller, et al., Corrosion Properties of Powder Bed Fusion Additively Manufactured 17-4 PH Stainless Steel, CORROSION, 73 (2017).

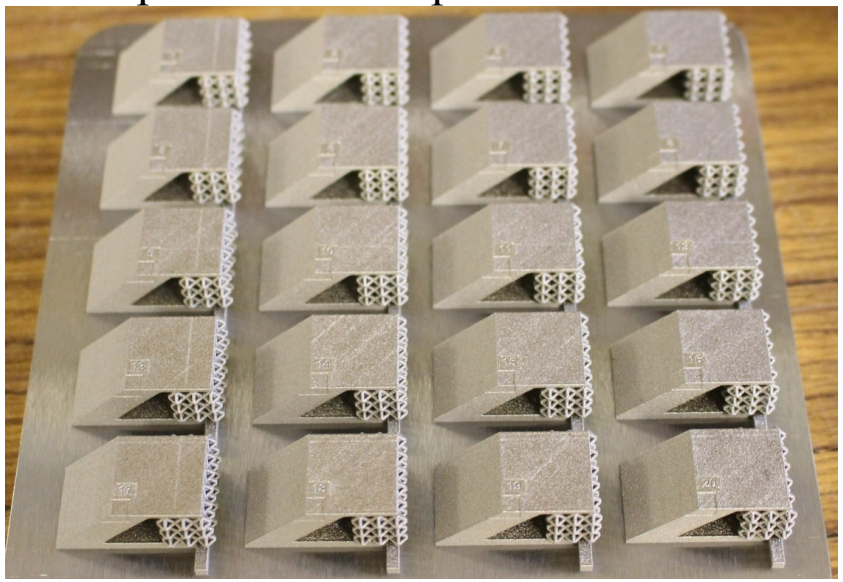
# Powder bed fusion 316L samples




Samples were prepared using 316L powder with a powder bed fusion (PBF) technique.



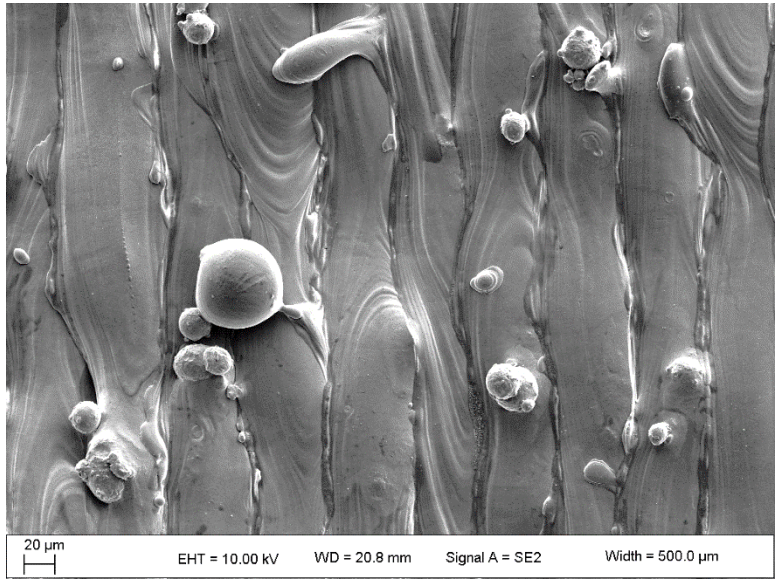
Build plate of 20 samples



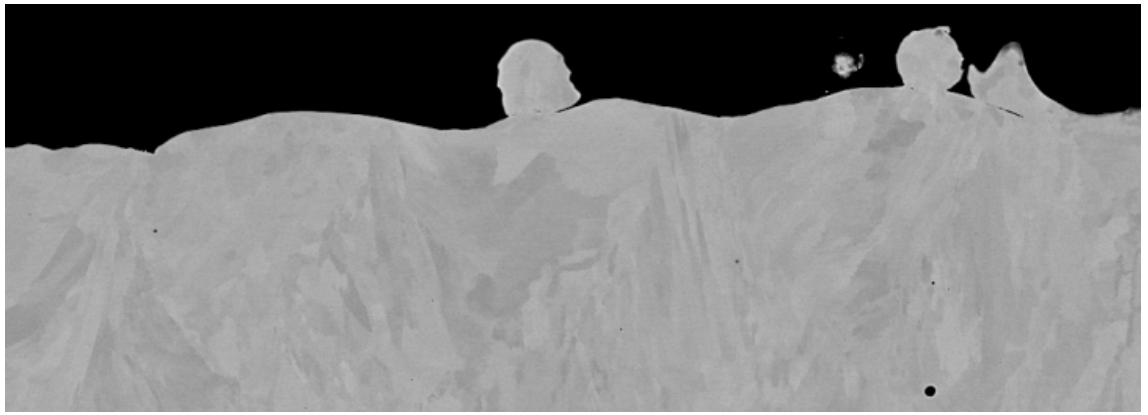
- Samples were printed on 5 different PBF machines, all with the machines optimized parameters for part density.

- SEM images of powder.
- Composition determined by ICP-MS and LECO.
- Powder analysis with laser diffraction.

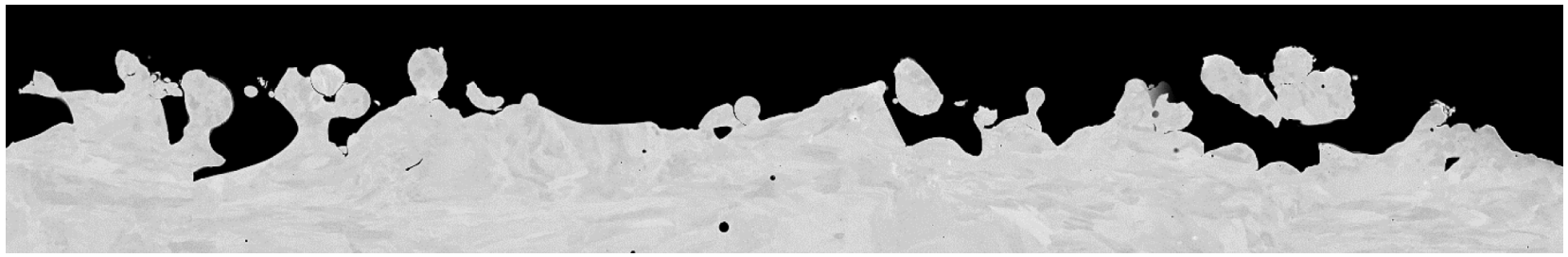
# What do as-printed surfaces look like?

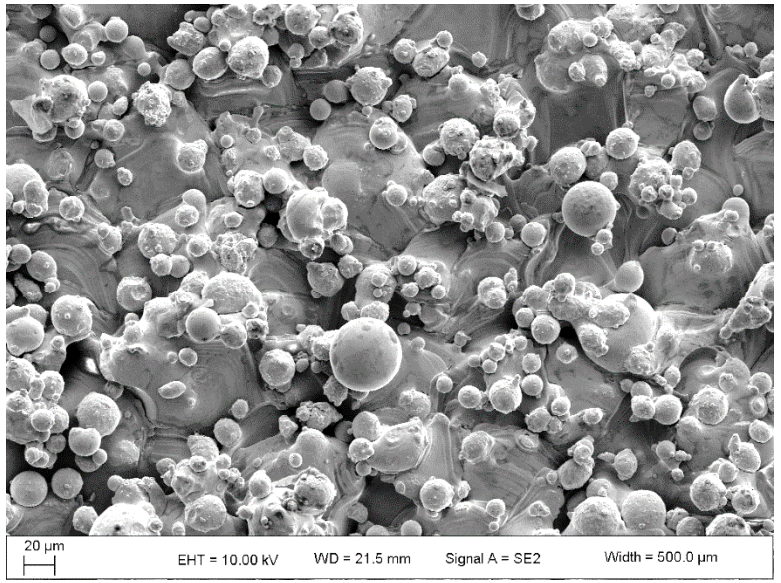



Top surface

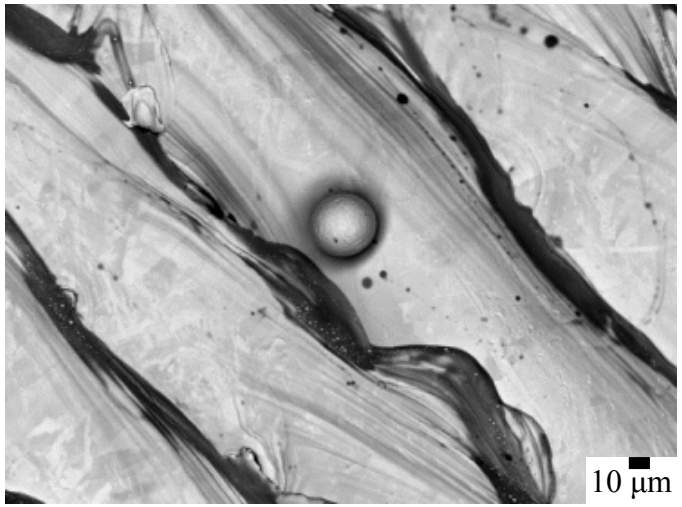


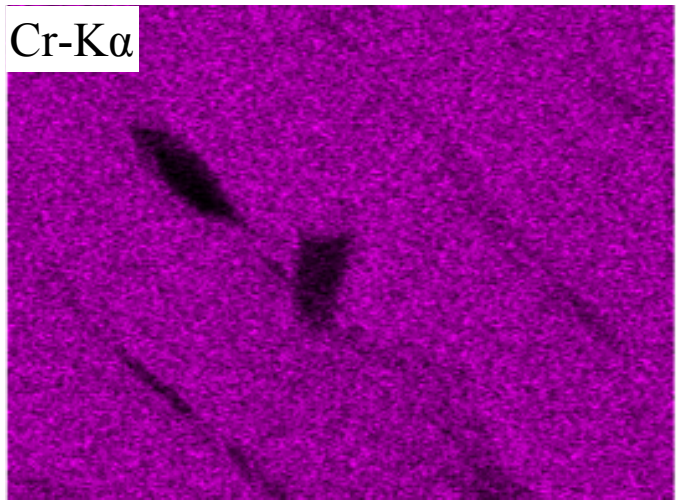
Side surface

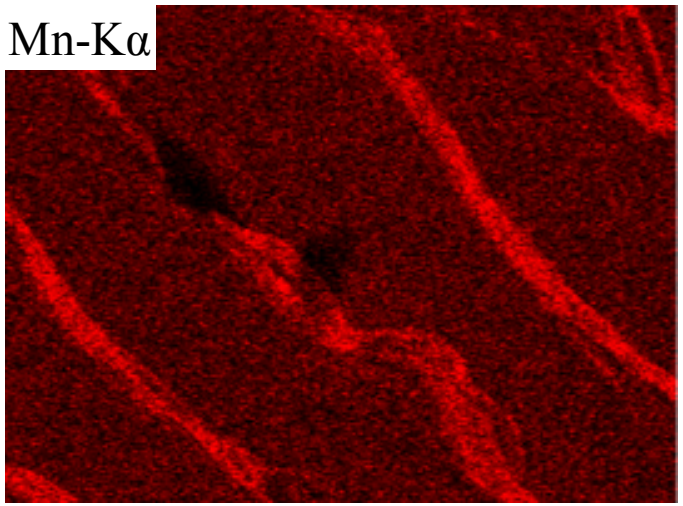


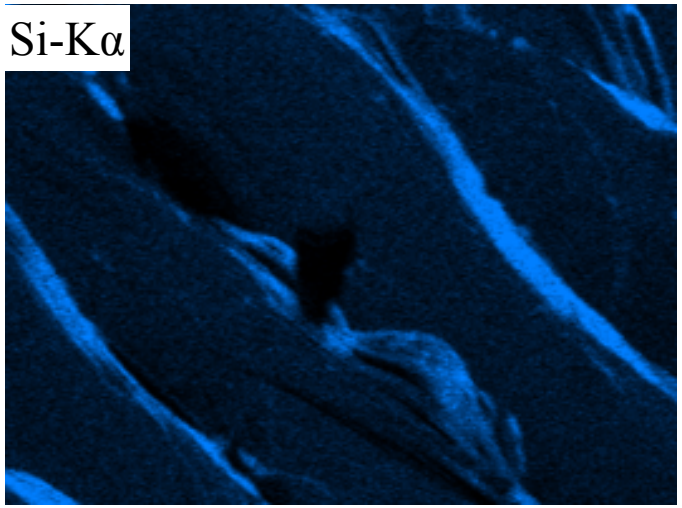


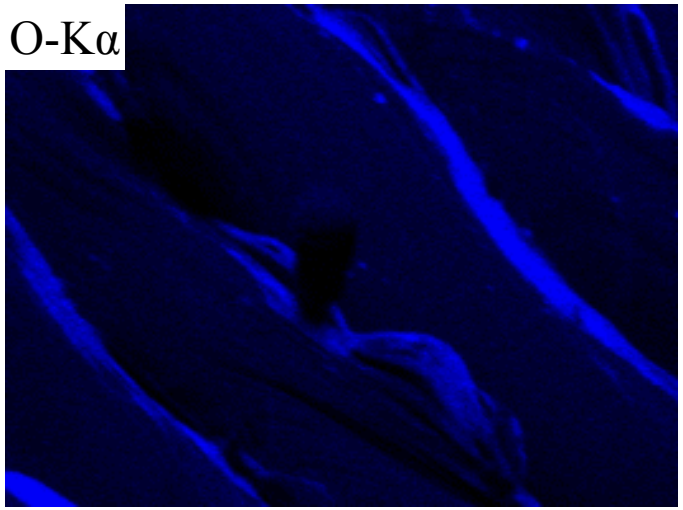
# EDS maps of as-printed top surface

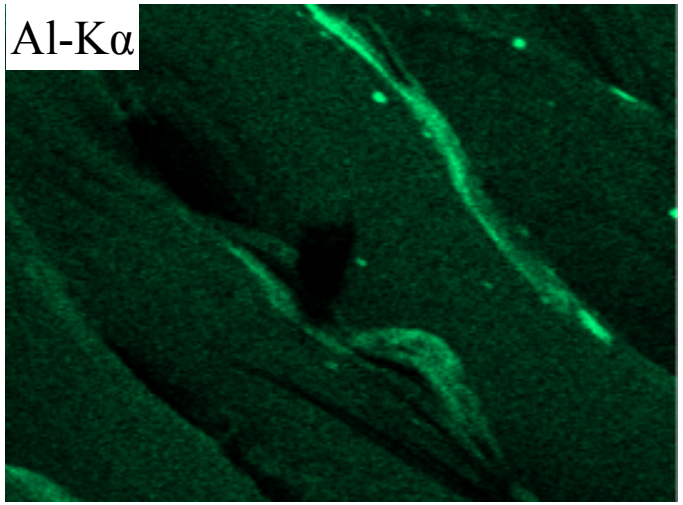


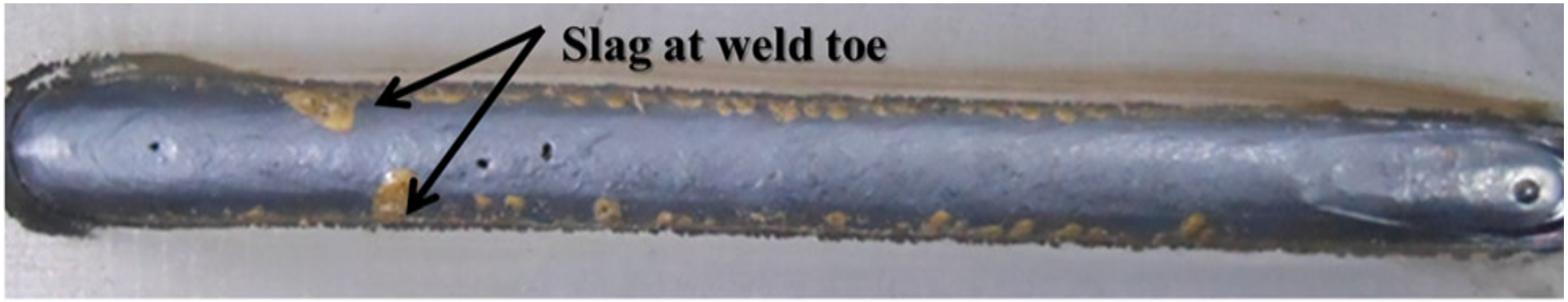



# Mechanism for the oxide formation

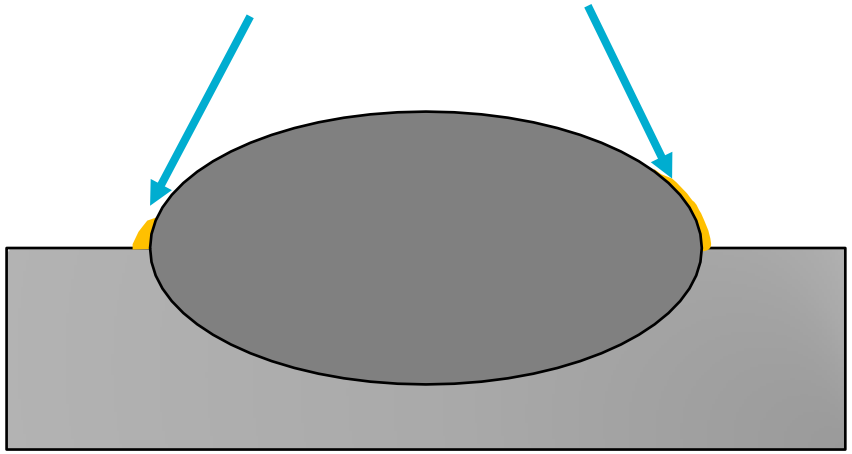
Cold metal transfer – gas metal arc welding




M.R.U. Ahsan, et al., Welding in the World, (2017). (a) Wire 1 (High Si, Mn)

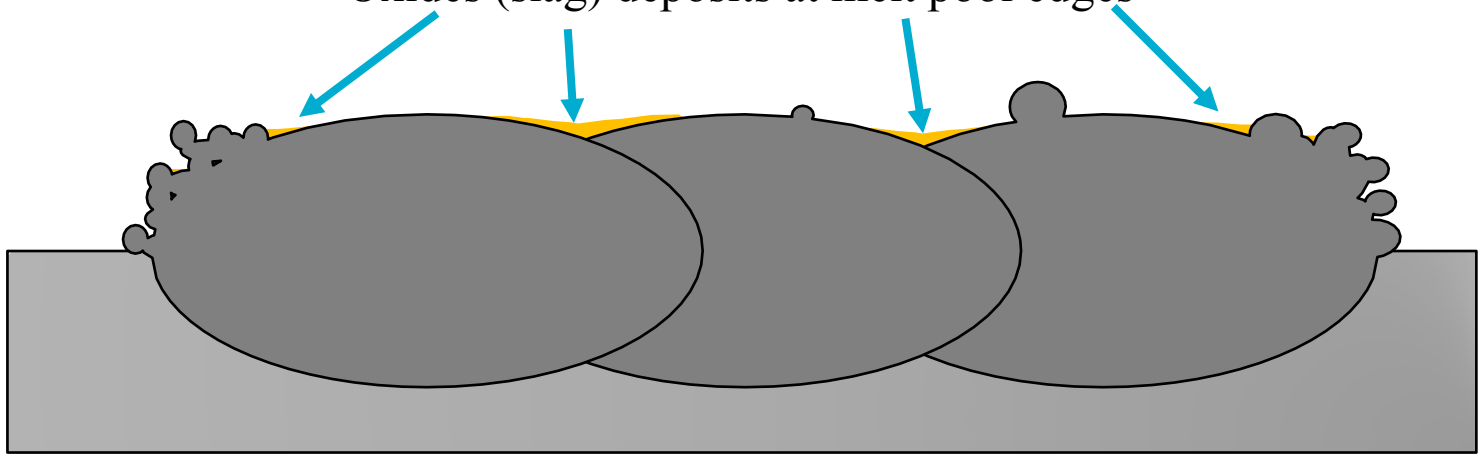
***The welding perspective.***

Oxides (slag) deposits at melt pool edges



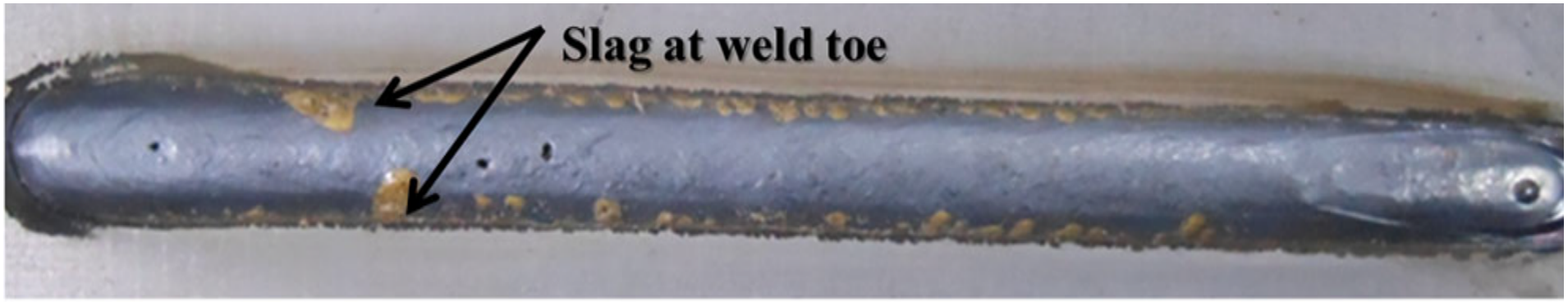
***The AM perspective.***

Oxides (slag) deposits at melt pool edges

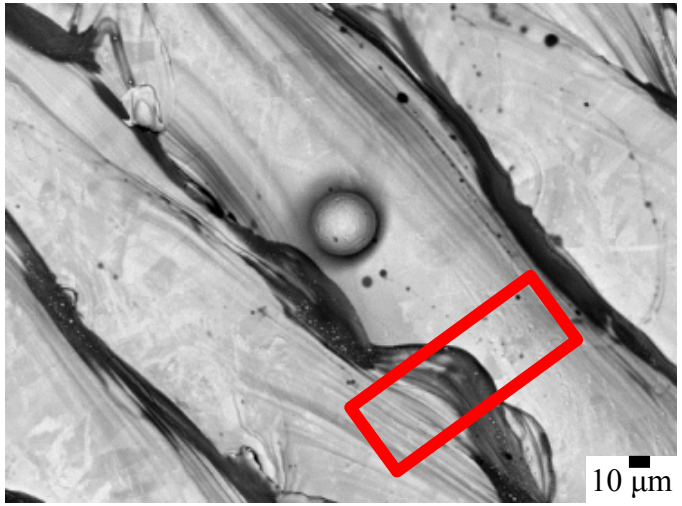


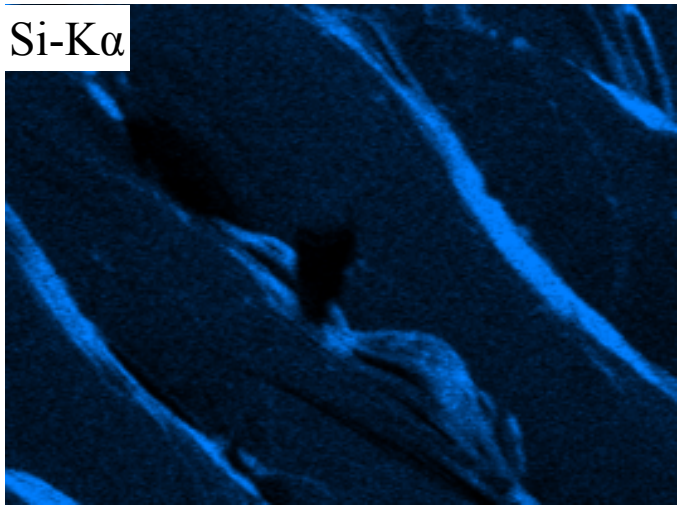
# Mechanism for the oxide formation

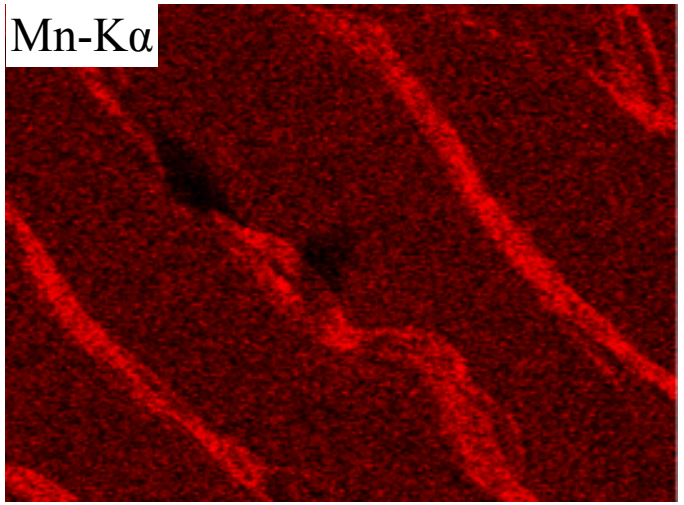
Cold metal transfer – gas metal arc welding



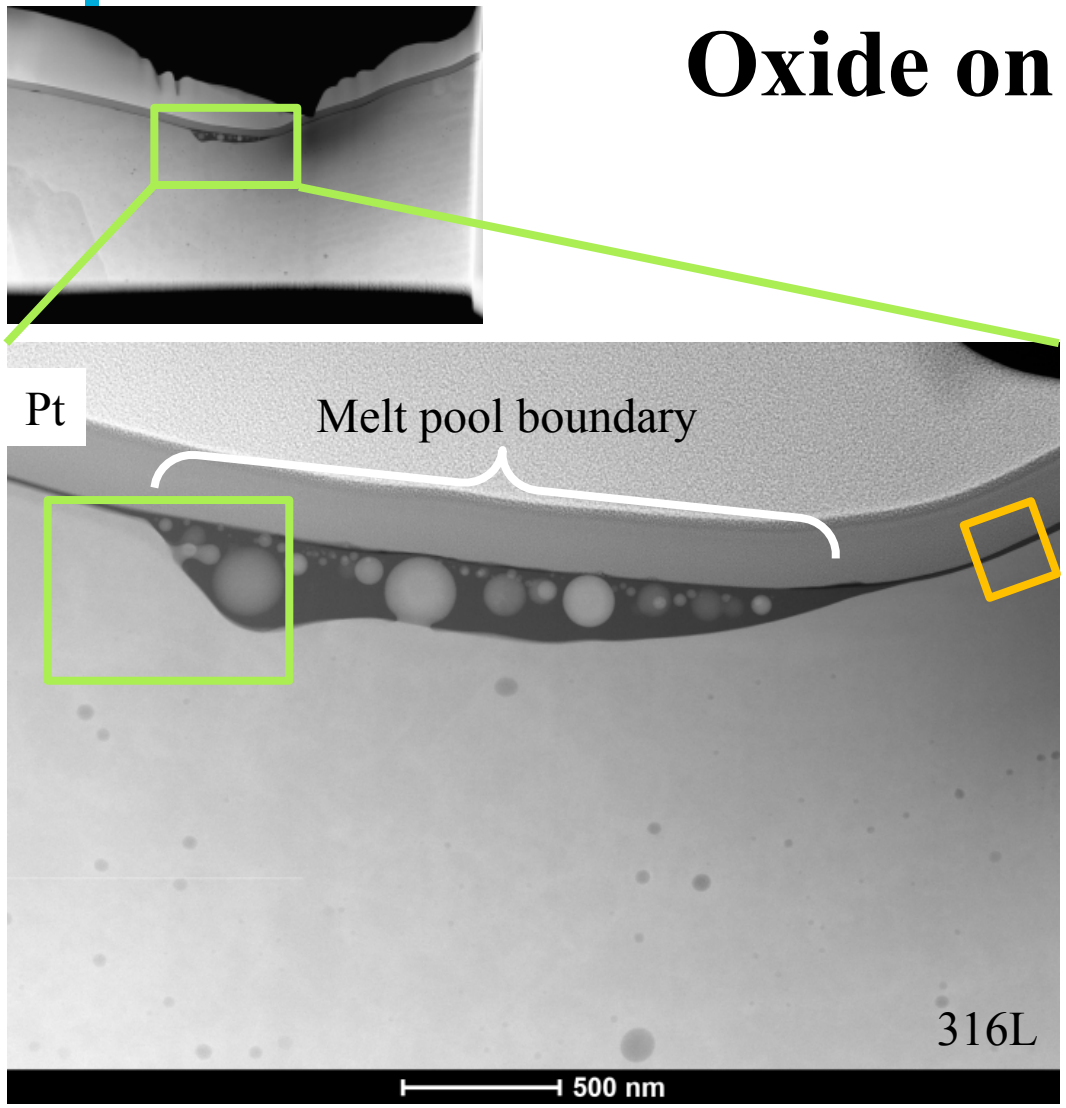

M.R.U. Ahsan, et al., Welding in the World, (2017). (a) Wire 1 (High Si, Mn)

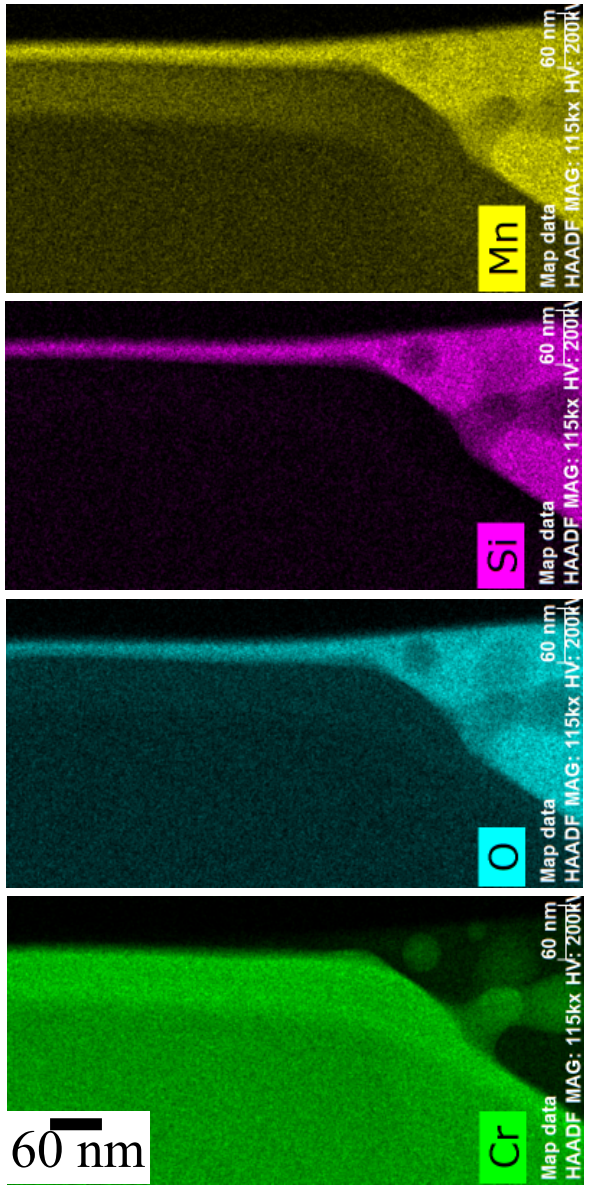


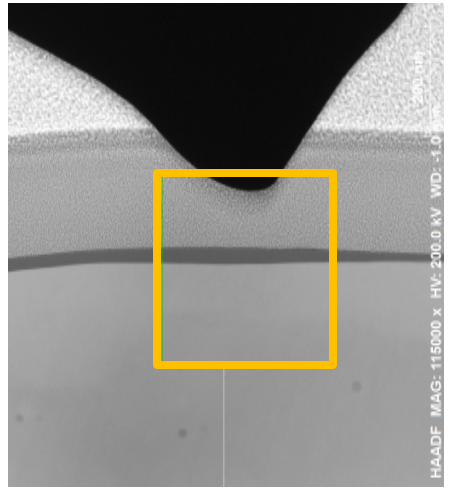



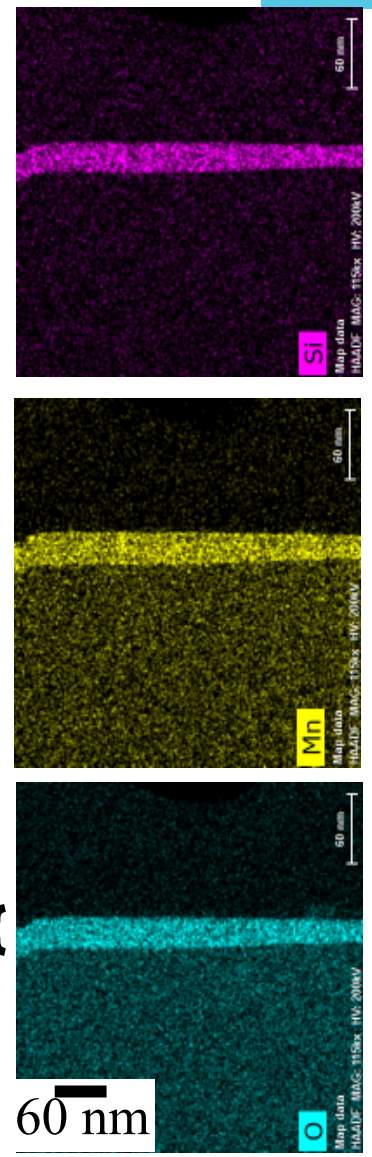
# Oxide on PBF 316L surface




To the right of boundary





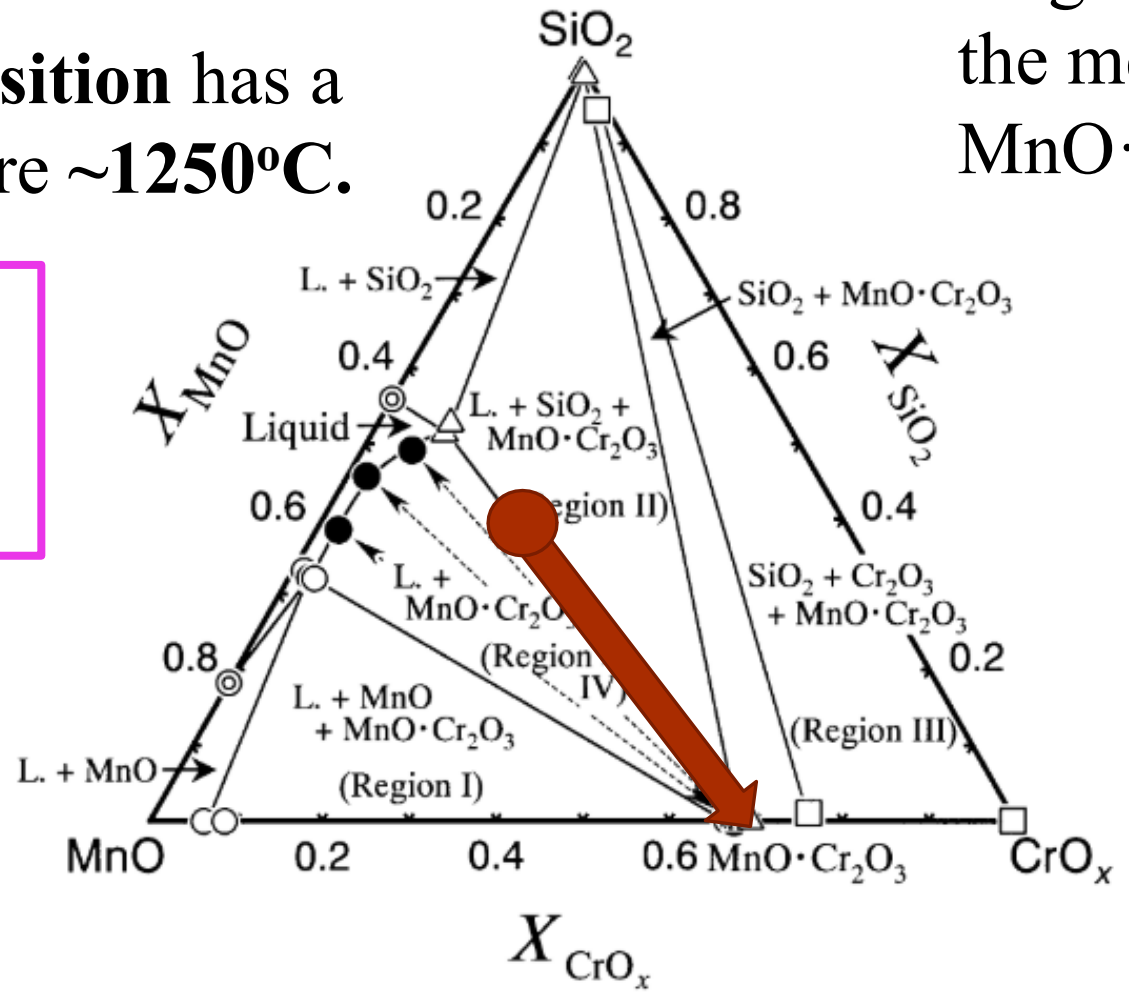

~25 nm {

# How and why do these oxides form?

This **oxide composition** has a melting temperature **~1250°C.**

**23% Cr**
**38% Mn**
**36% Si**

◎ Liquidus compositions at 1873 K in the $MnO$-$SiO_2$ binary phase diagram[2)]



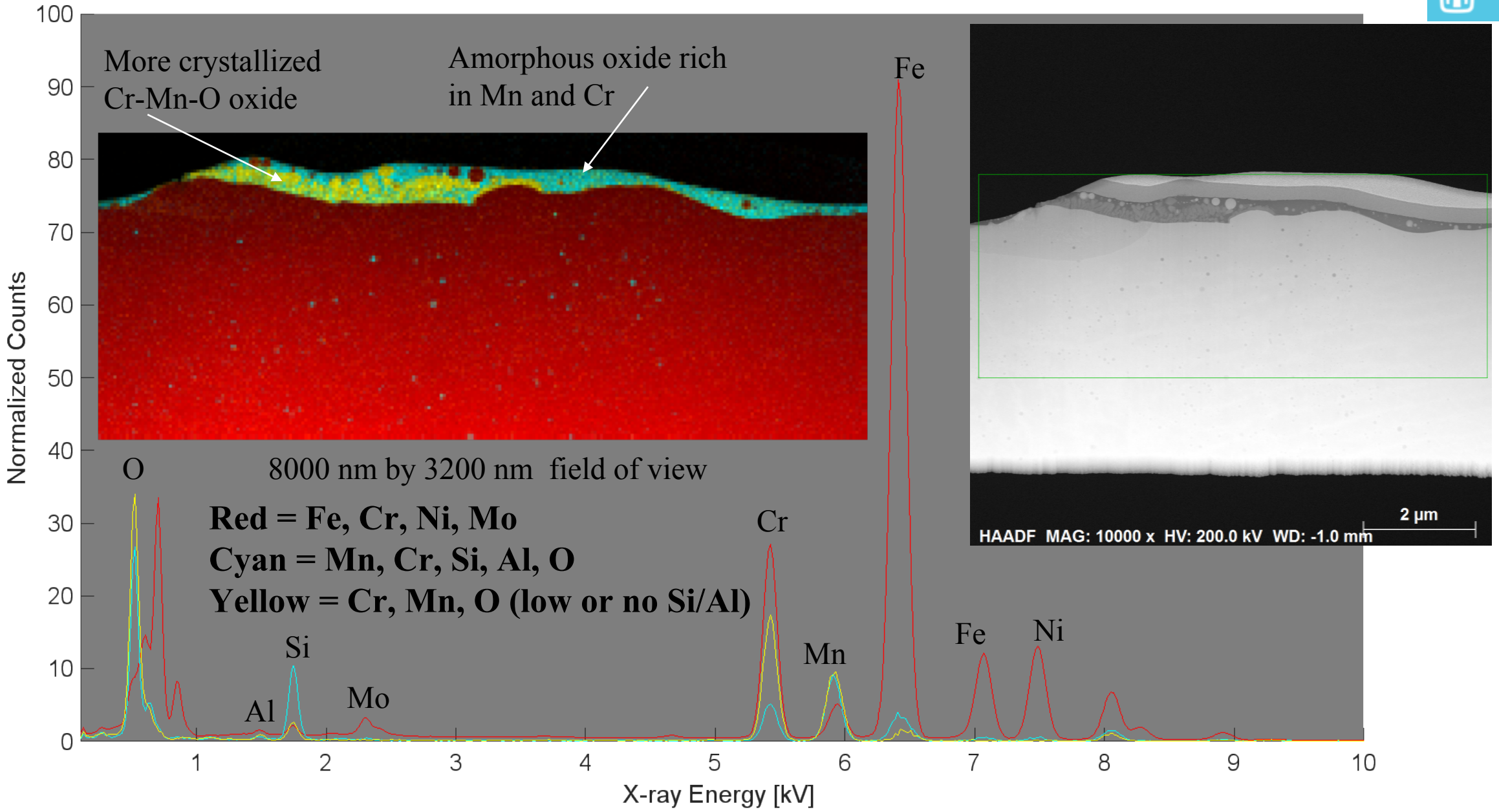

Ternary isotherm phase diagram at **1600°C** which is the melting temperature of $MnO \cdot Cr_2O_3$.

Melting temperature of **316L** is **~1350°C.**

($X_i$: Mole fraction of component i)

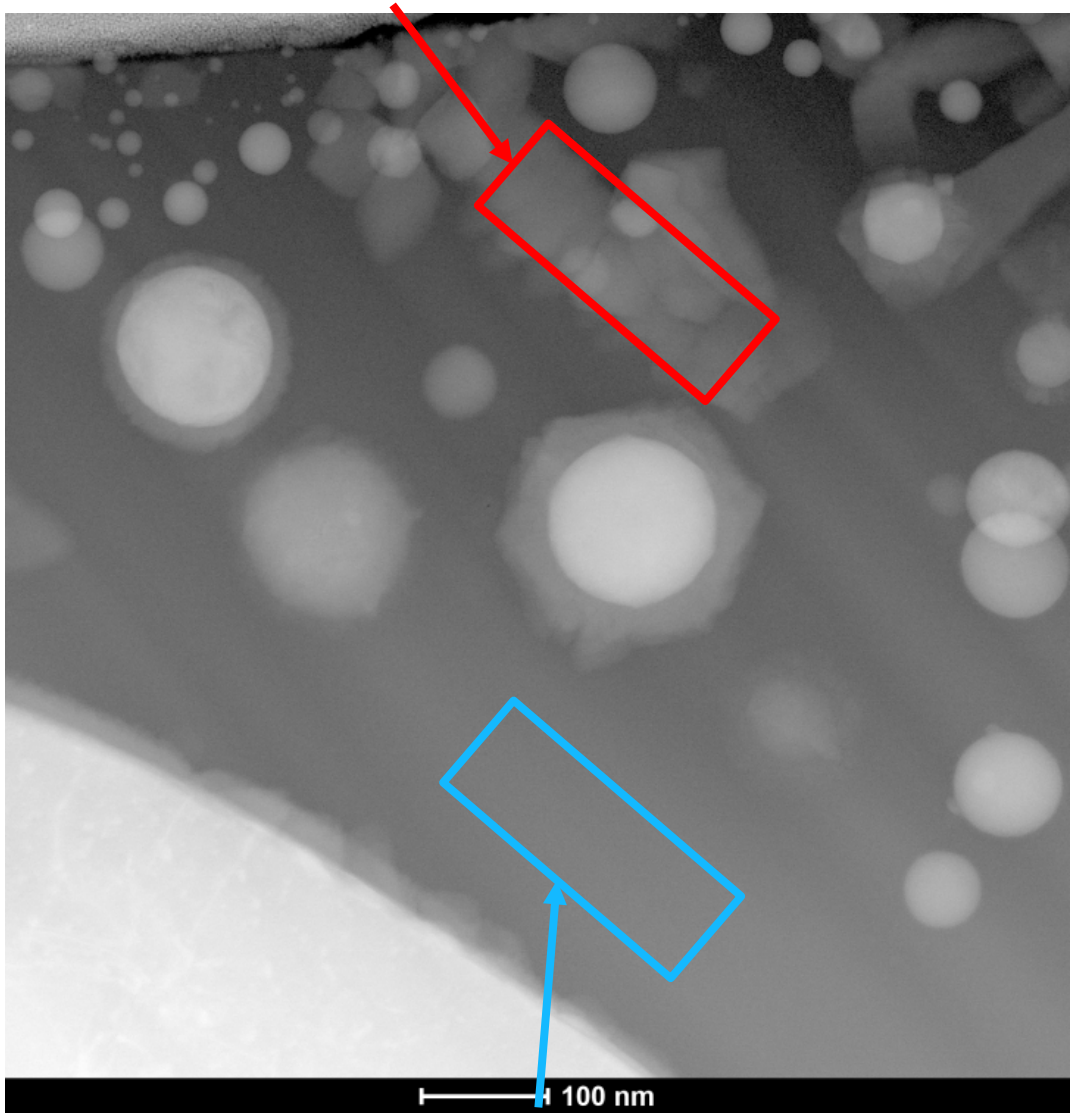
M. Tanahashi, et al., Phase Equilibria of the MnO, $SiO_2$, $CrO_x$ System at 1873 K under Controlled Oxygen Partial Pressure, ISIJ Int., (2001).

# Formation of Mn/Cr rich oxide



# How and why do these oxides form?

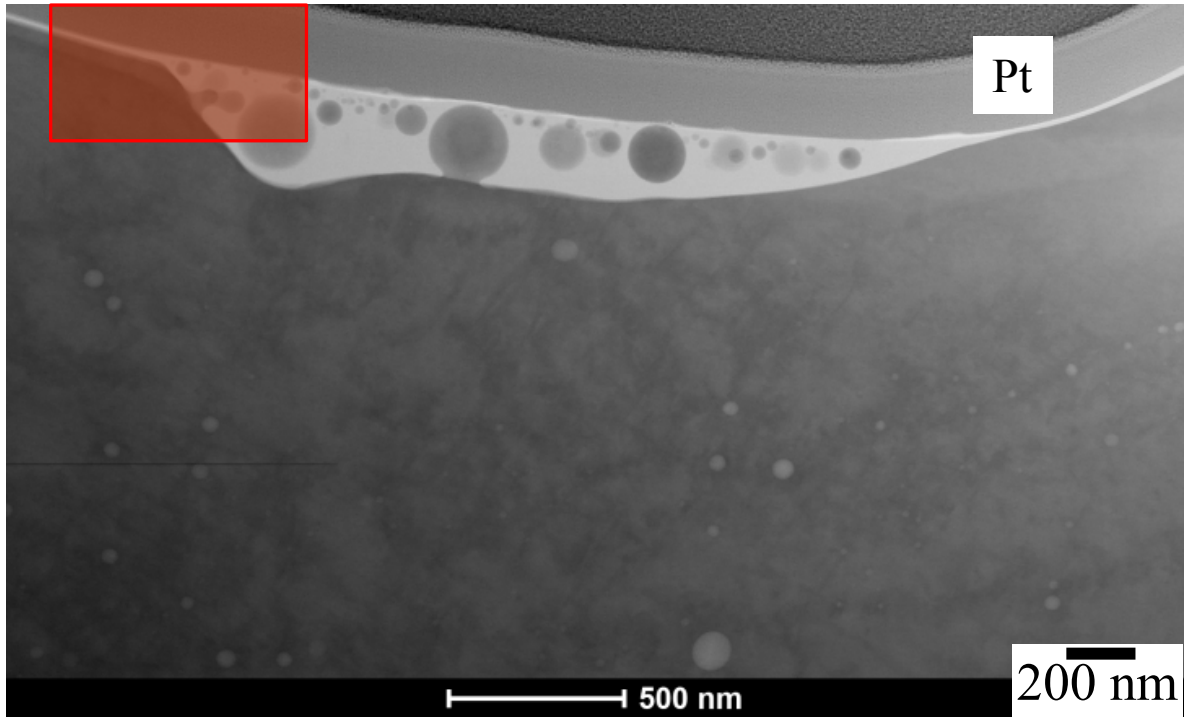
## 70% Cr-30% Mn oxide

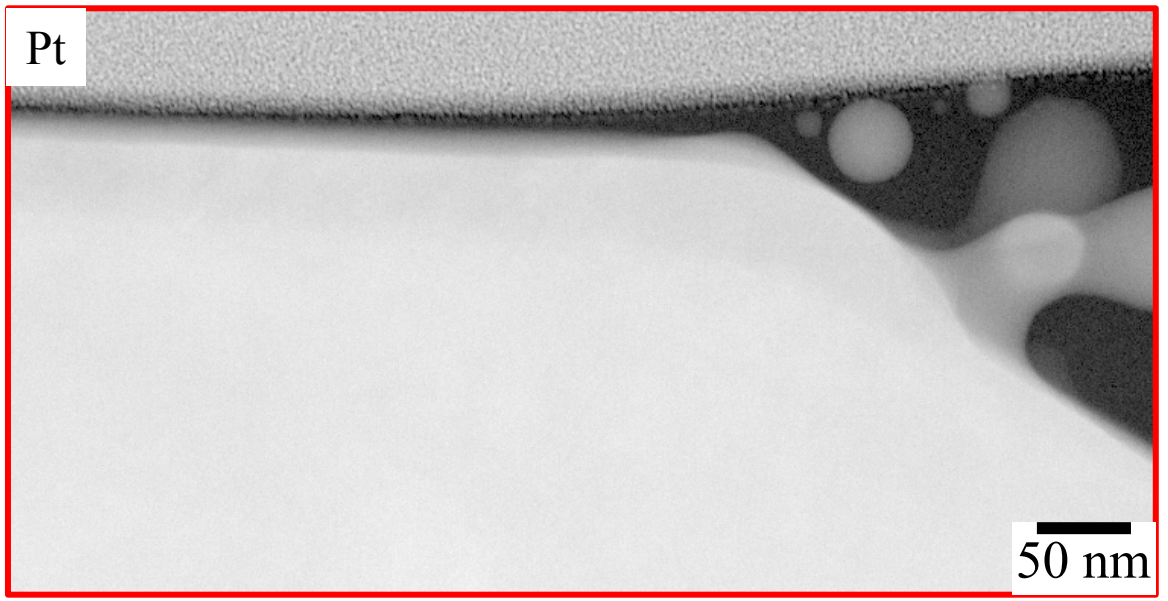



## 23% Cr-38% Mn-36% Si-3% Al

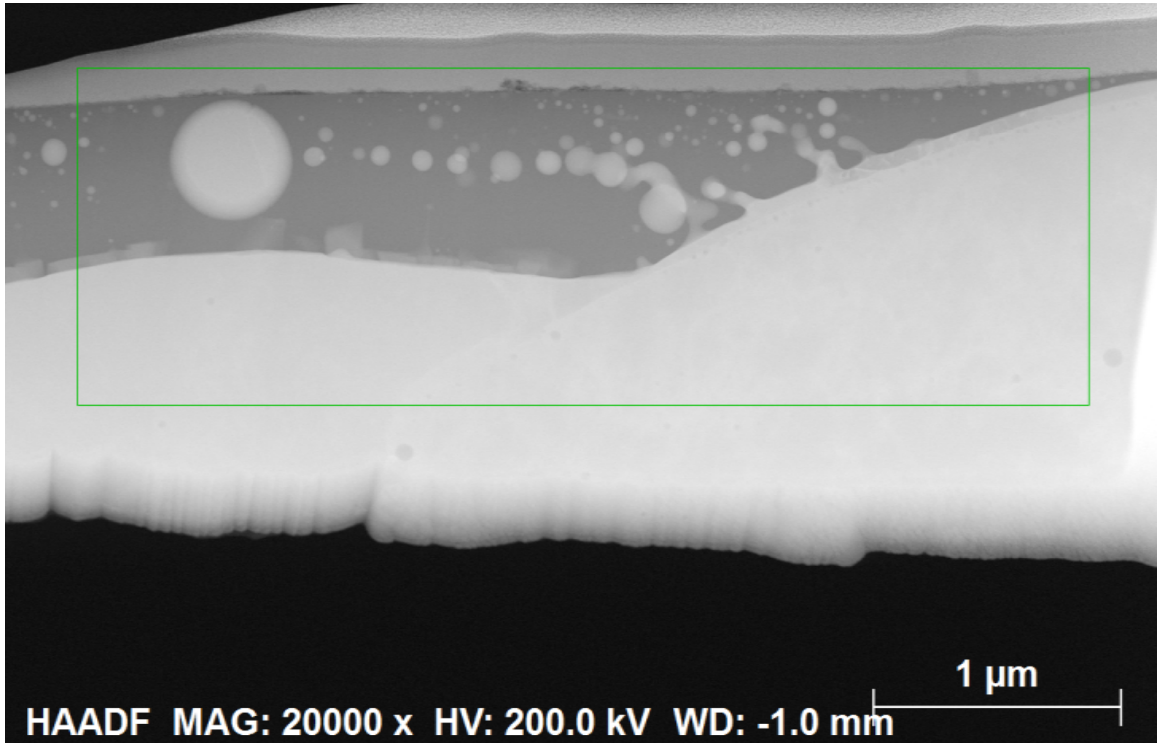
(UUR)

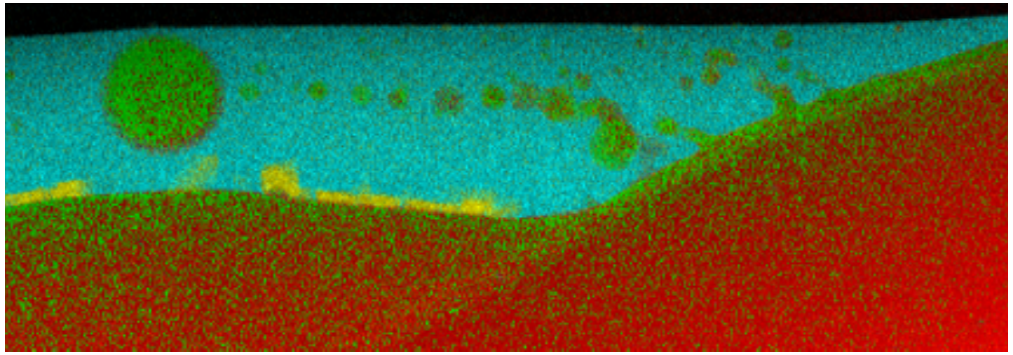
# Oxide on PBF 316L surface



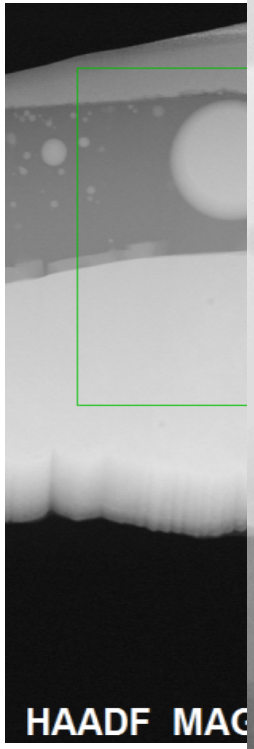
# Oxides on 316L surface from SLM280

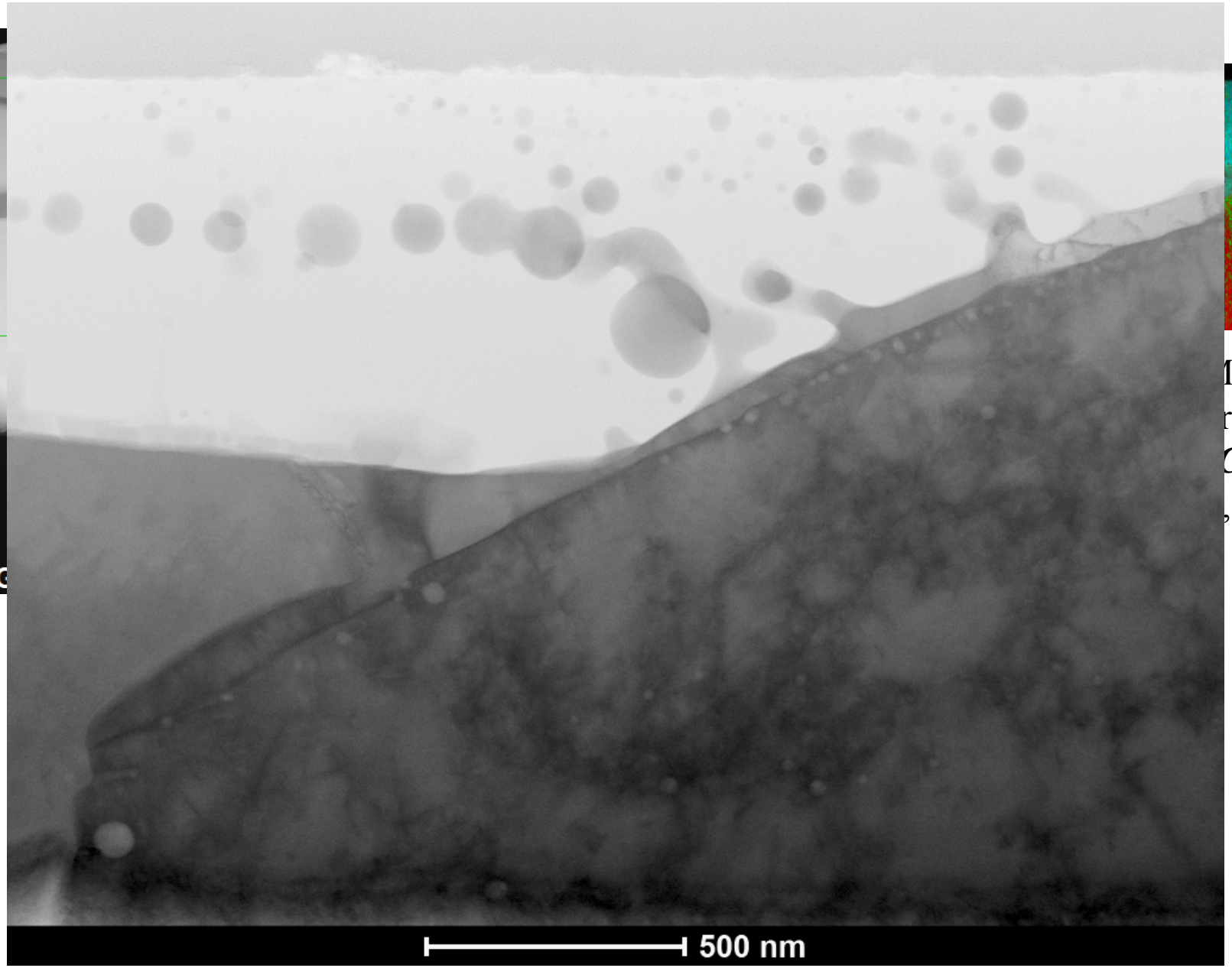


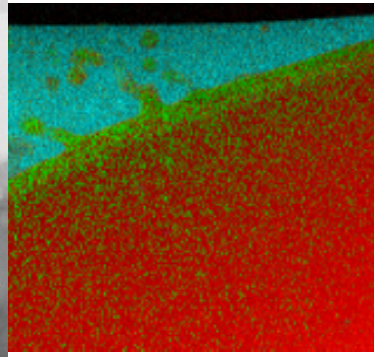



Red = Fe, Cr, Ni, Mn, Mo
Green (Yellow) = Cr enriched
***Cyan = Mn, Cr, Si, Ti, Ca, Al, O***
Yellow = Cr, Mn, Ti, Si, Al, O

# Oxides on 316L surface from SLM280



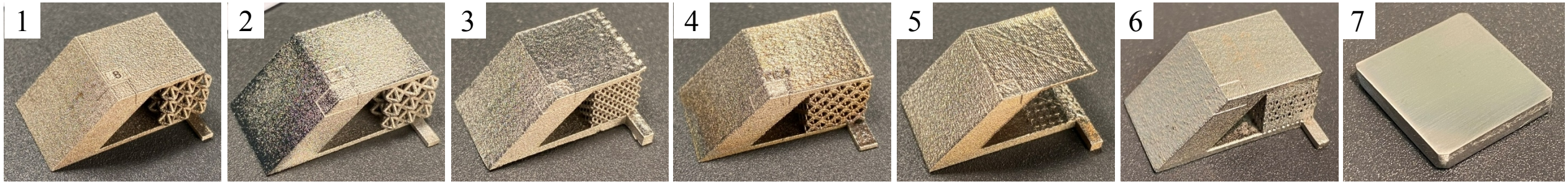
lo
riched
*Ca, Al, O*
, Al, O

# The as-printed surface of 316L stainless steel

- The oxide on the surface primarily forms via a slag formation mechanism.
  - Lower density oxides (primarily Mn/Si/Cr/Al rich) float to the surface of the liquid melt pool, agglomerate, and deposit at the melt pool edge. (All phases can be in liquid state during this).
- The oxide is an amorphous Mn Silicate, enriched in Cr (melting temp ~ 1250$^{o}$C).
  - A crystalline phase rich in Cr/Mn (minimal Si/Al) should form at equilibrium in the Mn Silicate liquid with a melting temperature of 1600$^{o}$C.
  - Cr/Mn rich oxide is only found in some cross-sectioned samples.
- Emulsification process creates spheres of stainless steel metal, “floating” in the amorphous oxide – likely happens when both the metal and Mn Silicate are liquid above 1400$^{o}$C.

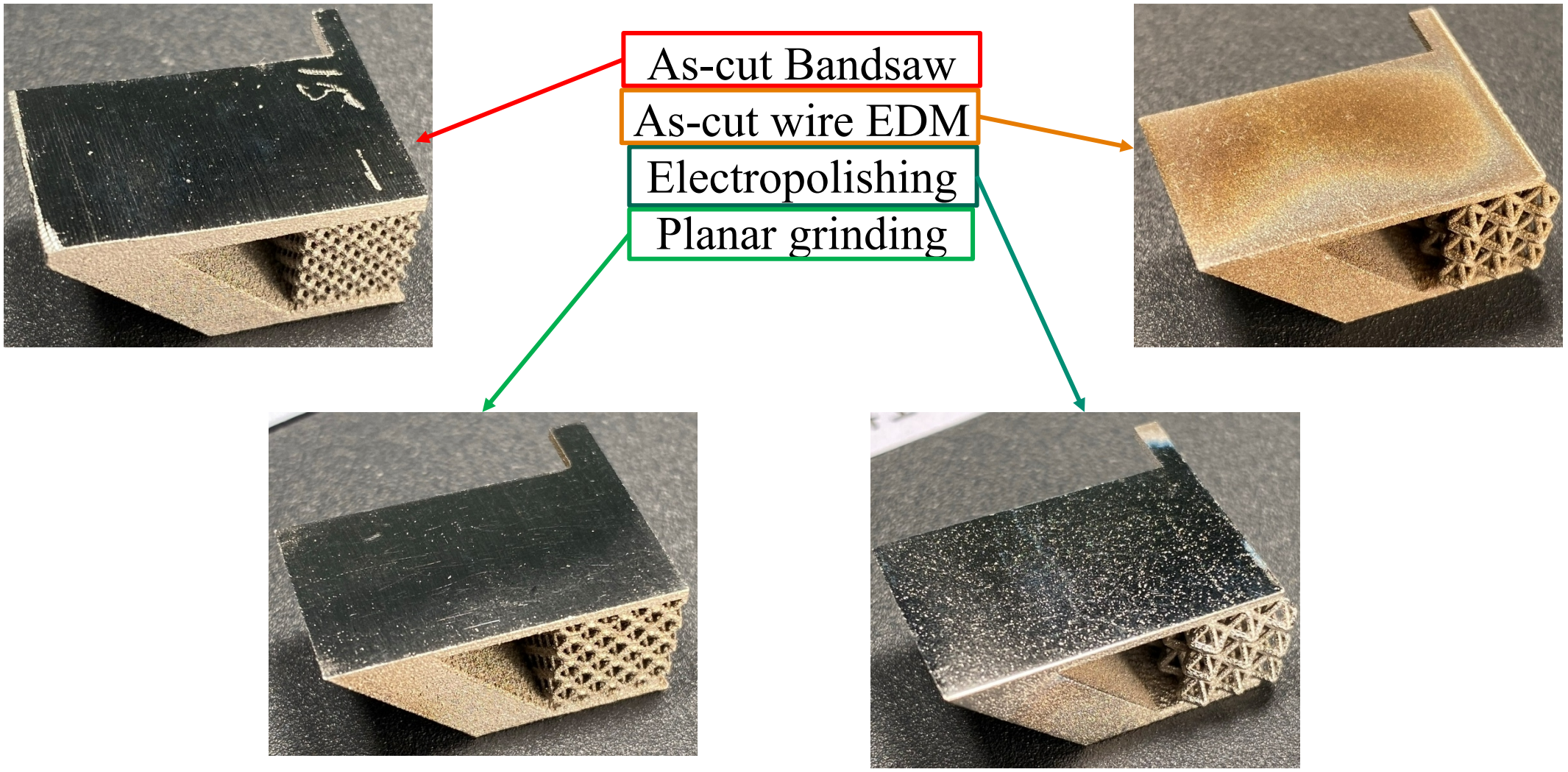
# ASTM G85-A2: Sample ID

1st set – ProX200 As-printed – *wire EDM cut surface*
2nd set – ProX200 – *Electropolished*
3rd set – EOS M290 As-printed – *Bandsaw cut surface*
4th set – Renishaw AM250 As-printed – *Polished with 600 grit sand paper*
5th set – SLM280 As-printed – *wire EDM cut surface*
6th set – Concept Laser M2 As-printed – *Bandsaw cut surface*
7th set – Wrought 316L – *Fine grinding with 600 grit sand paper*




Courtesy of Danyil Kovalov (UVA)

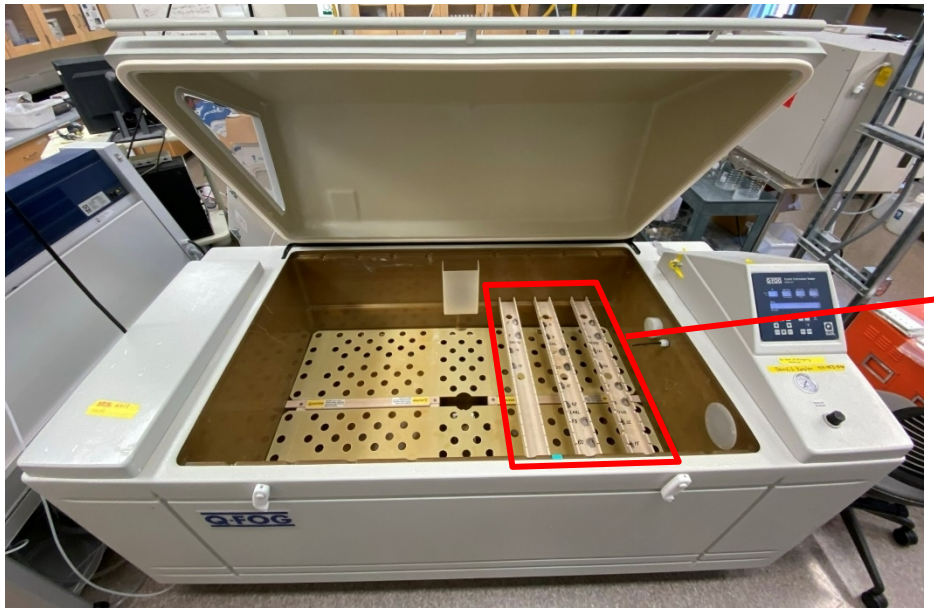
# ASTM G85-A2: Sample ID

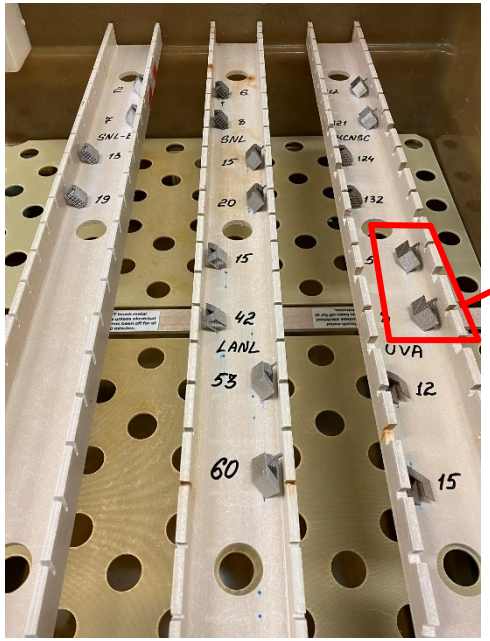


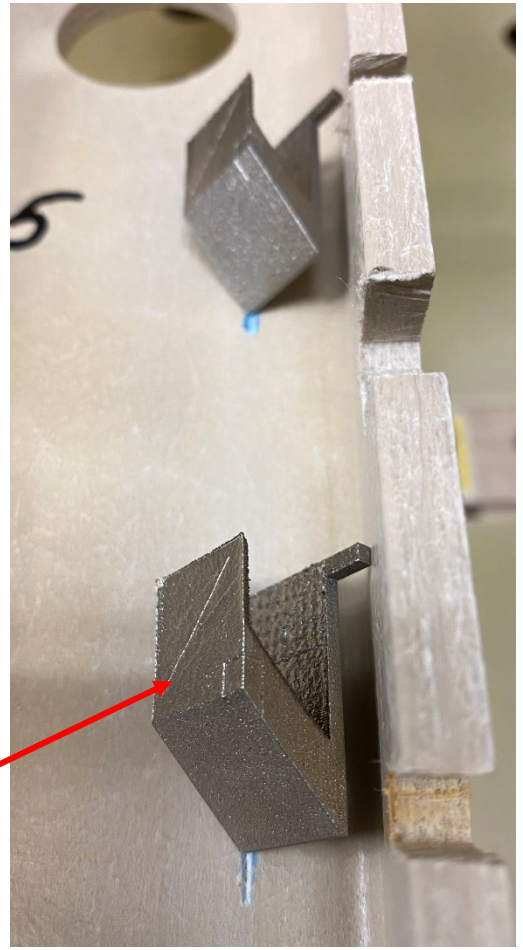

Courtesy of Danyil Kovalov (UVA)

# ASTM G85-A2: Setup

- **ASTM for sample testing: G85 A2 with wet bottom**
- Equipment: Q-fog cyclic corrosion tester.
- Solution: 0.9M NaCl acidified to pH 3 with acetic acid.
- Test temperature: 49°C.
- Duration: 2000 hr.
- Sample holder: PEEK rack with milled paths to place AM 316 samples.

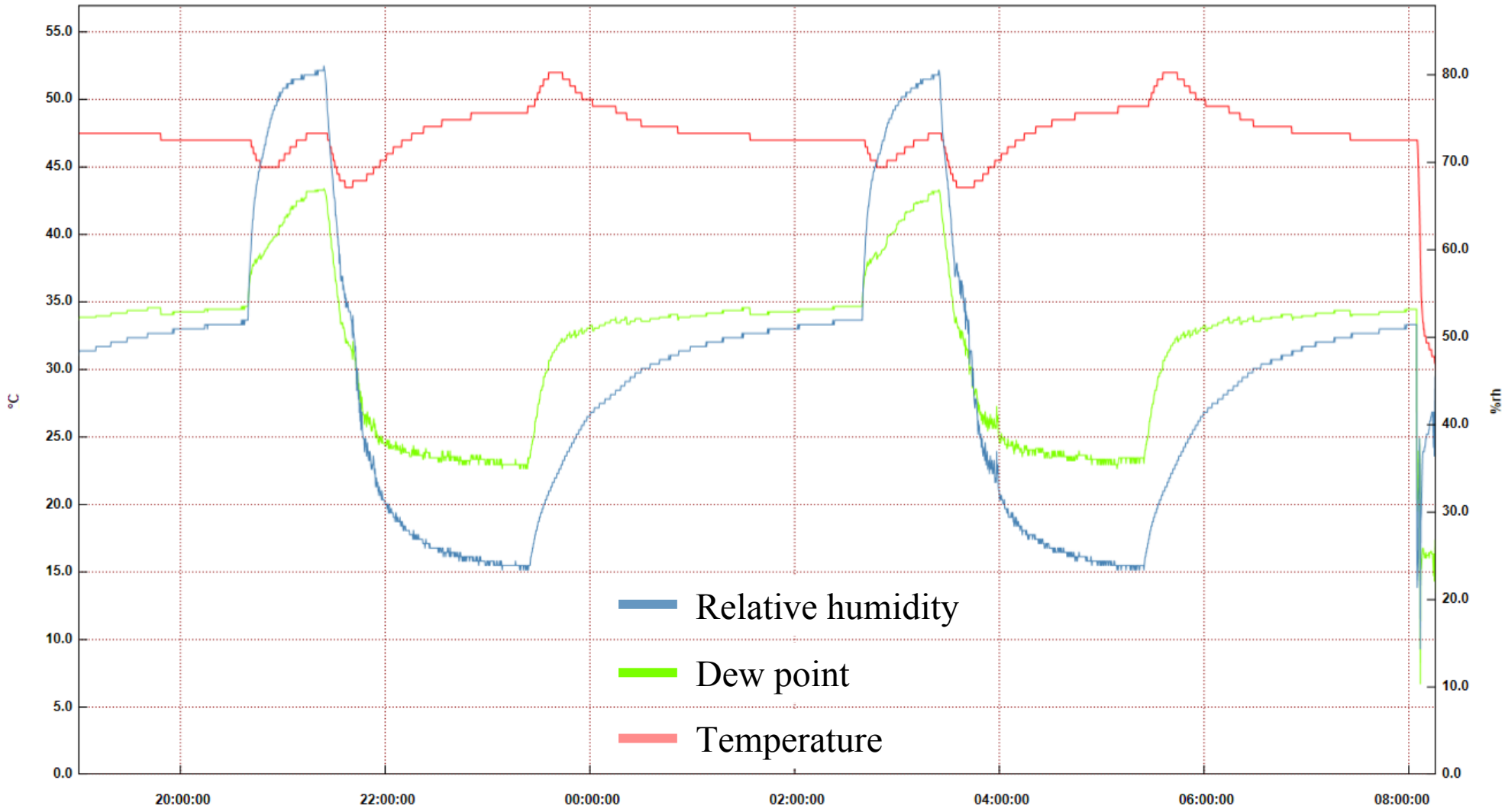


(UUR) Courtesy of Danyil Kovalov (UVA)

# ASTM G85-A2: RH and Temp.

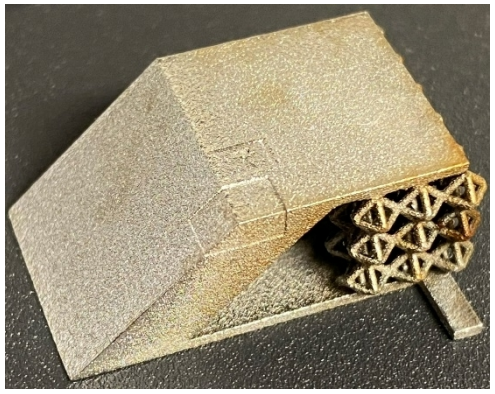



(UUR) Courtesy of Danyil Kovalov (UVA)

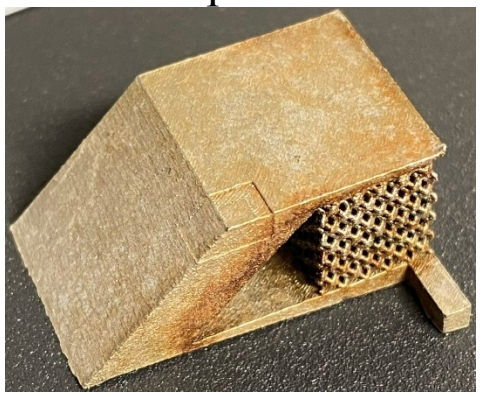
# Samples after 2000 hours – Top down

ProX 200
As-printed

ProX 200
Electropolish

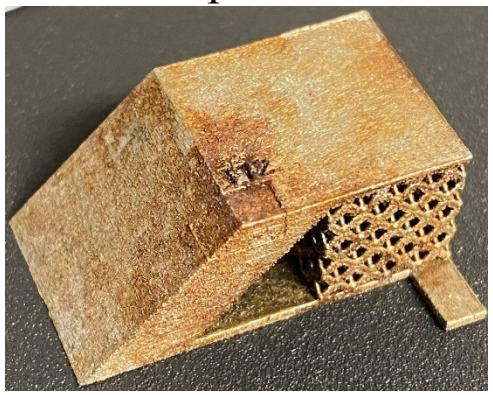


EOS M290
As-printed

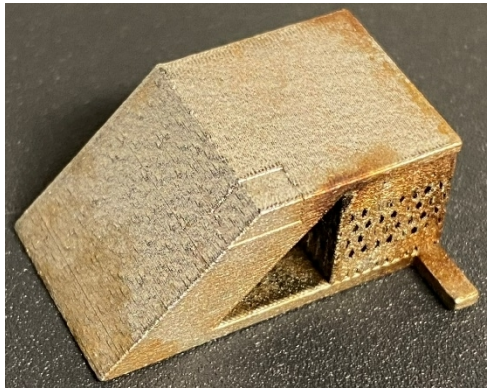


Wrought surface
was polished

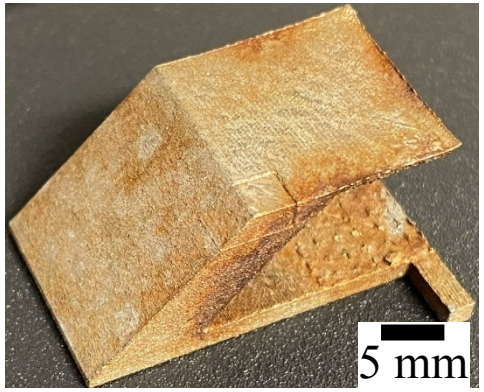
Renishaw
As-printed



Concept M2
As-printed



SLM®280
As-printed

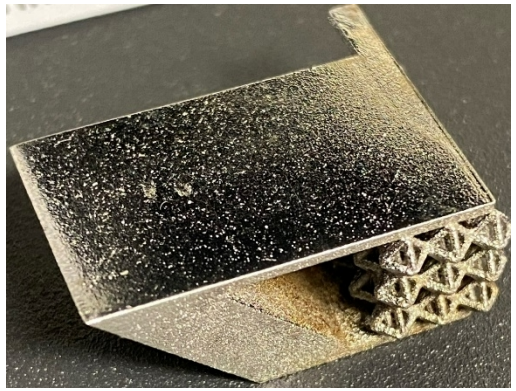



(UUR) Courtesy of Danyil Kovalov (UVA)

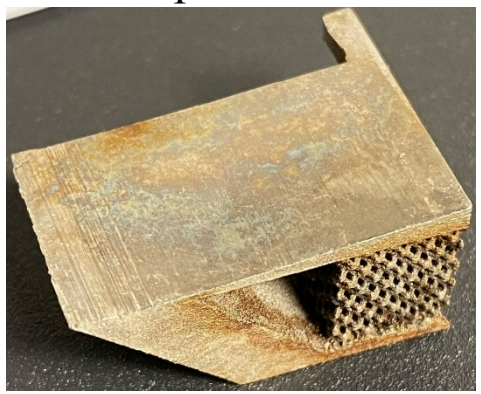
# Samples after 2000 hours – Cut surface

ProX 200
As-printed

ProX 200
Electropolish

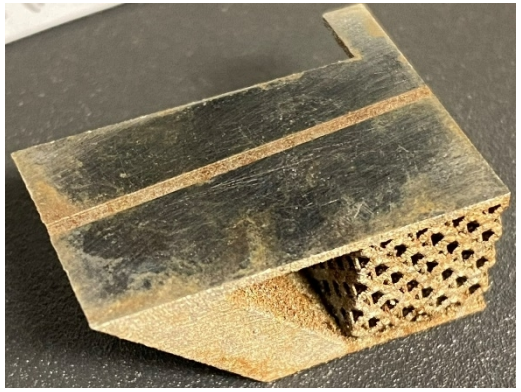


EOS M290
As-printed

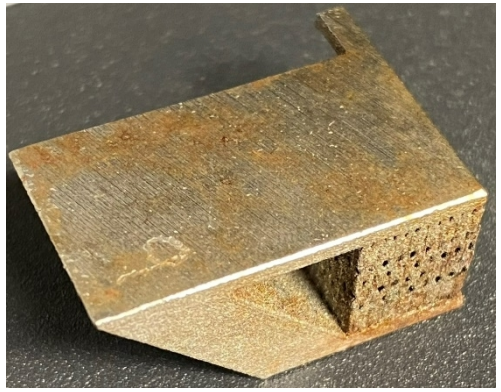


Wrought surface
was polished

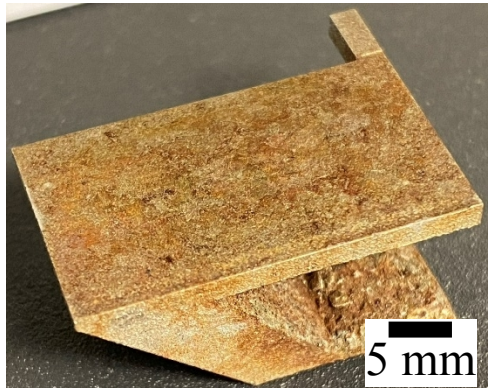
Renishaw
As-printed



Concept M2
As-printed



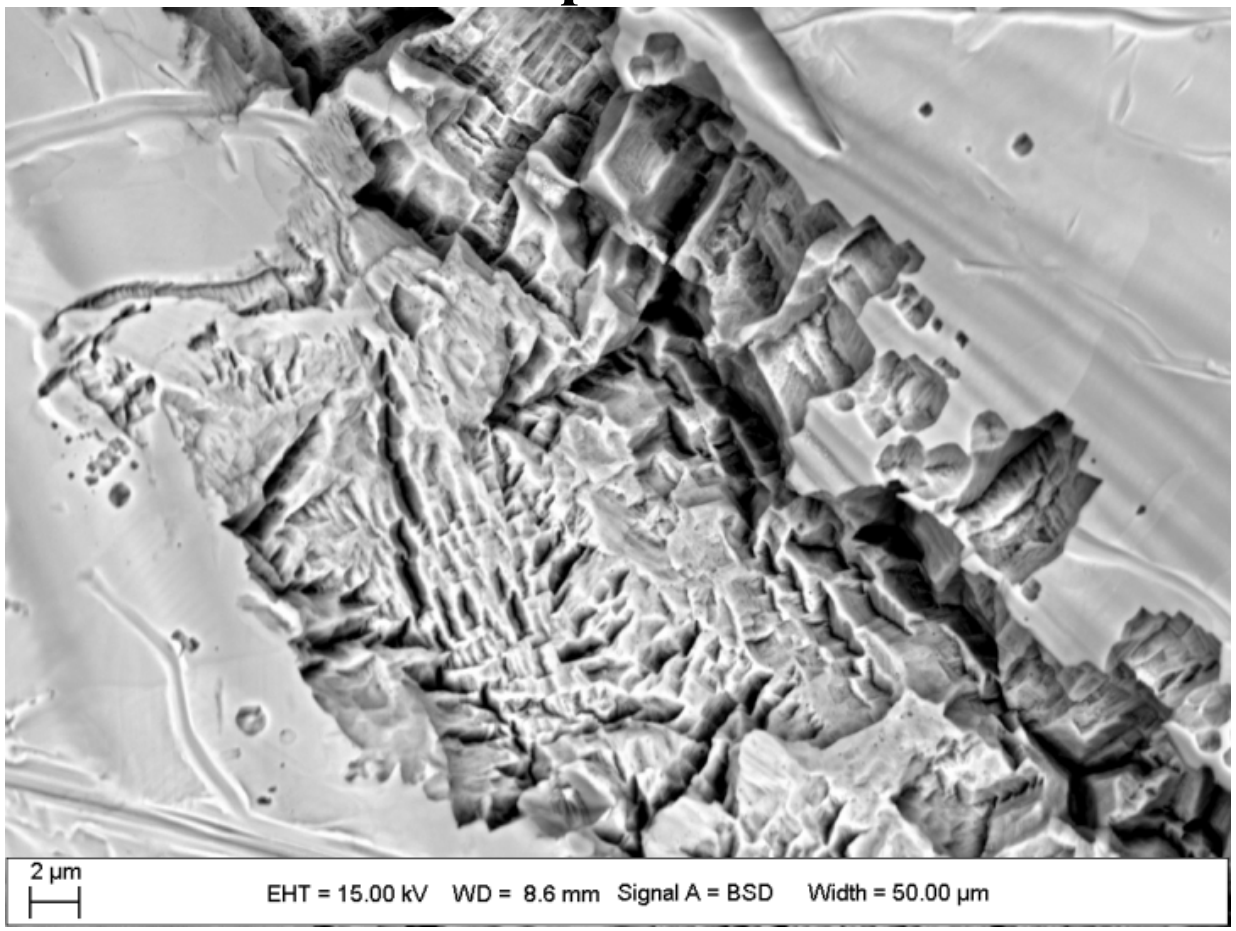
SLM®280
As-printed



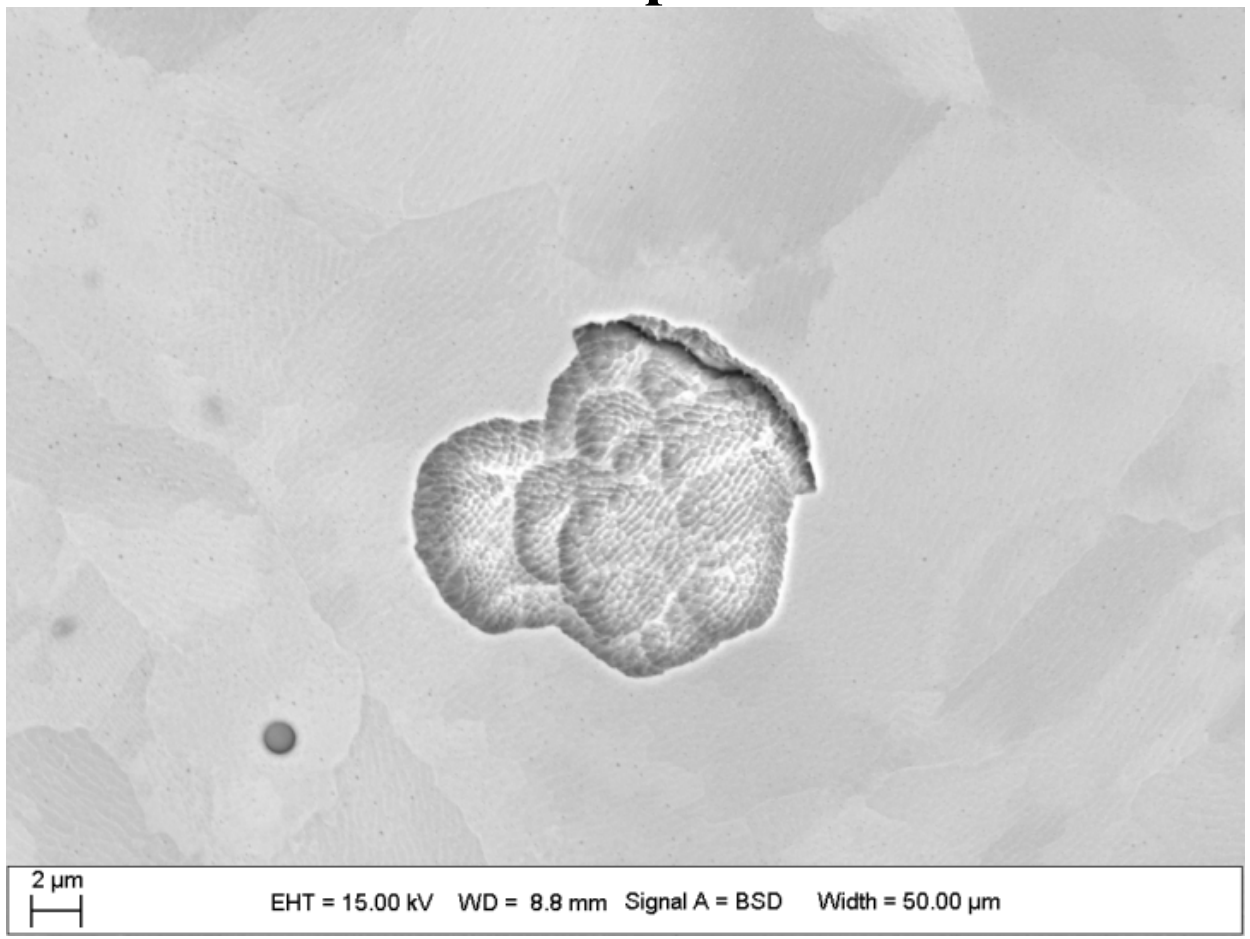

Courtesy of Danyil Kovalov (UVA)

# Pit morphology

ProX 200
**As-printed**



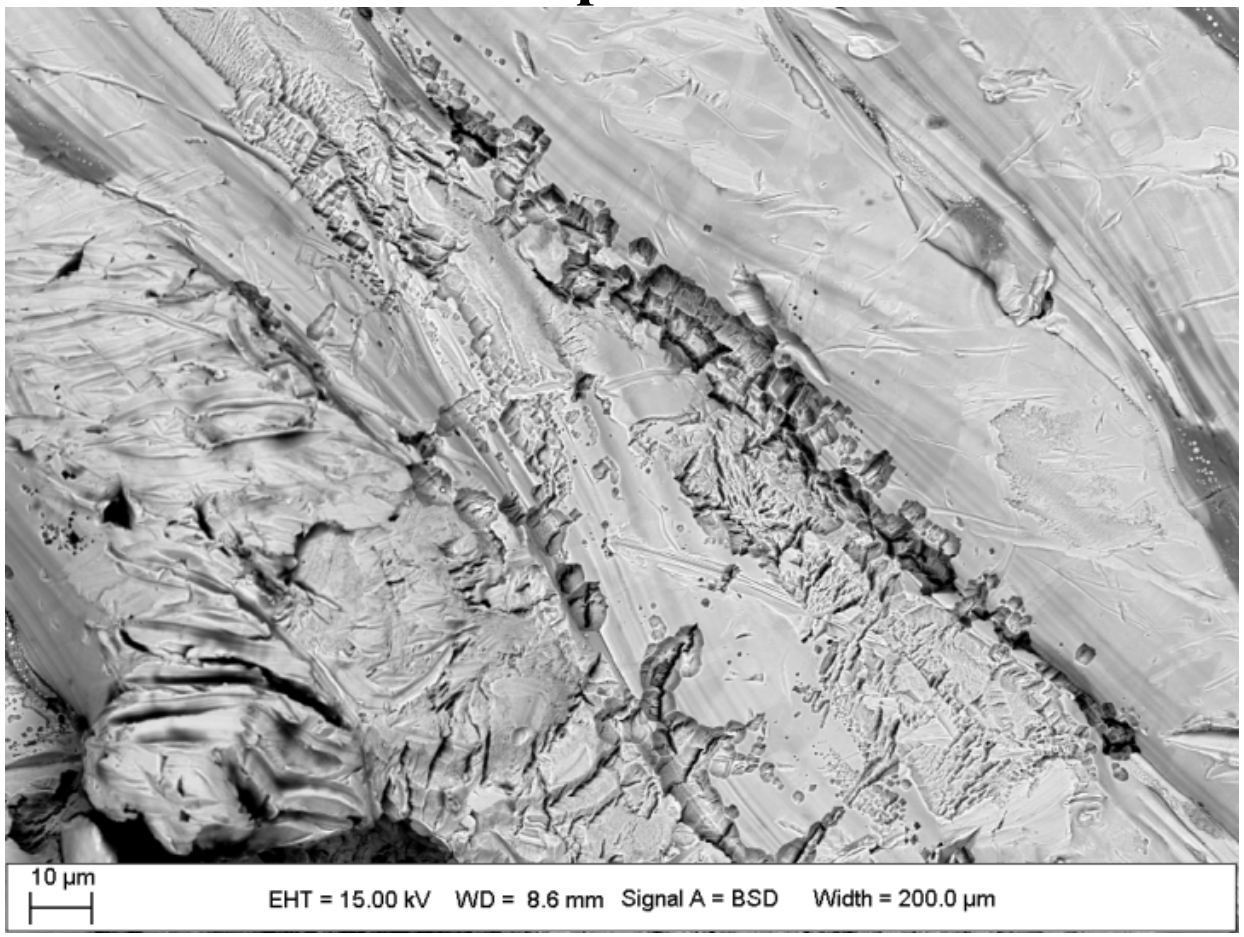

ProX 200
**Electropolish**



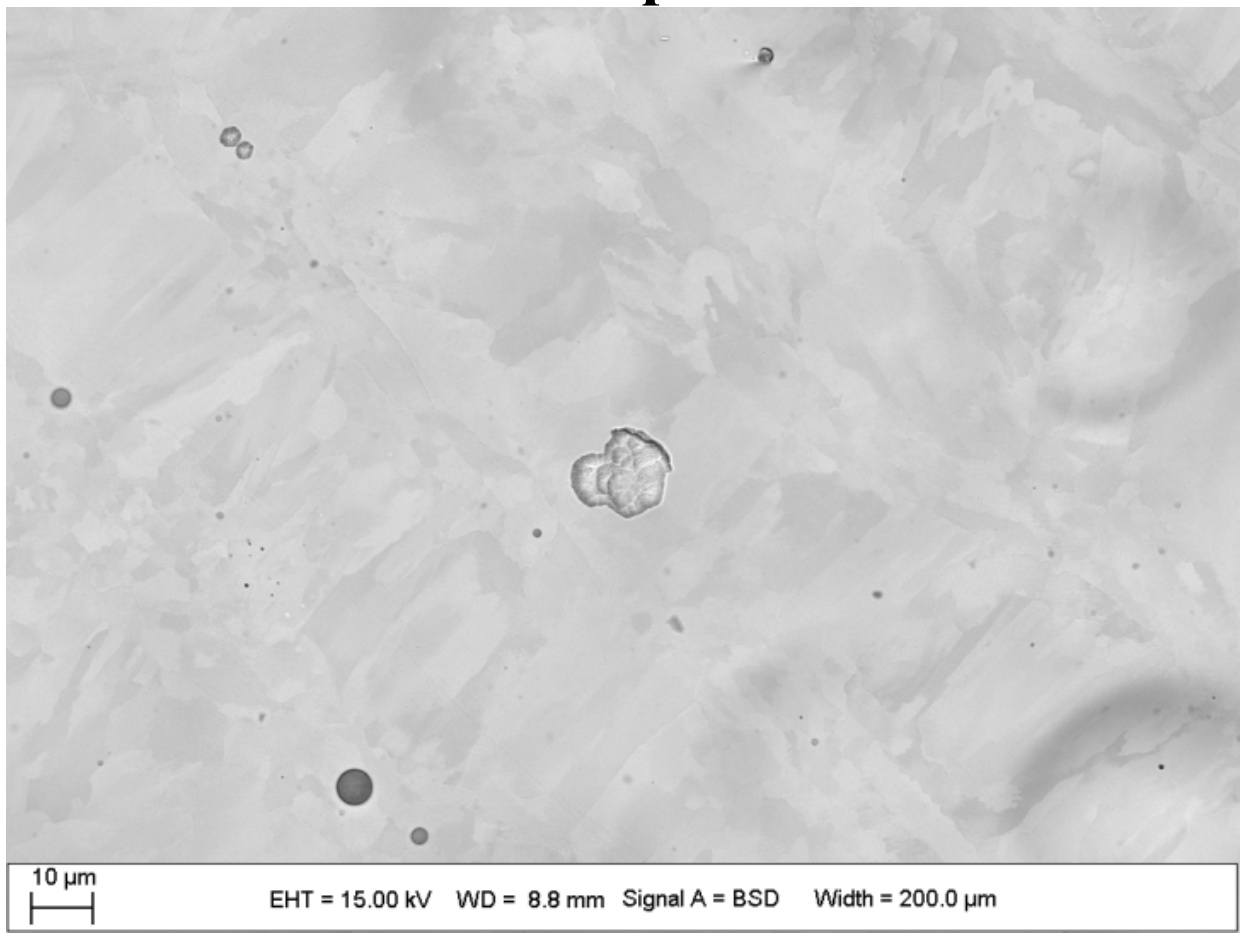

(UUR) Courtesy of Luis Jauregui (SNL)

# Pit morphology

ProX 200
**As-printed**



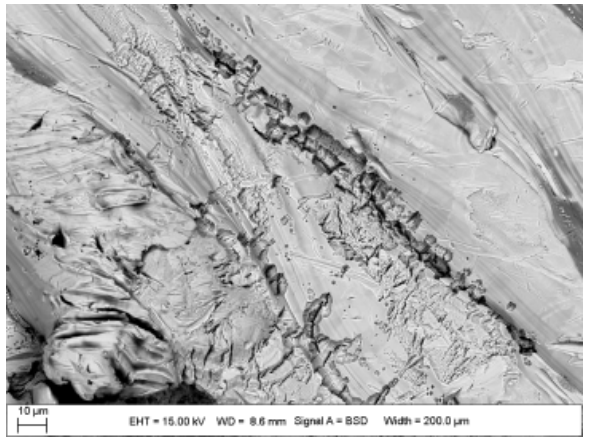

ProX 200
**Electropolish**



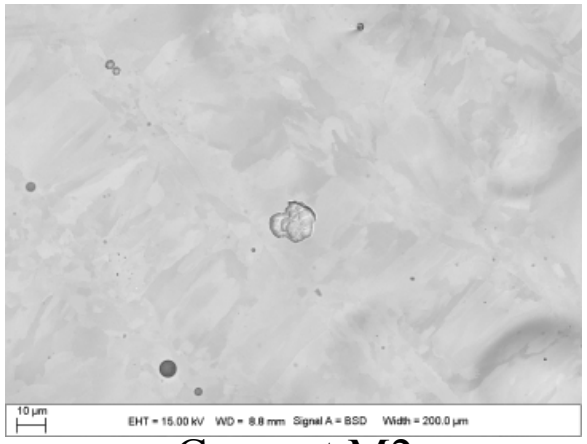

 Courtesy of Luis Jauregui (SNL)

# Pit morphology – Top surface

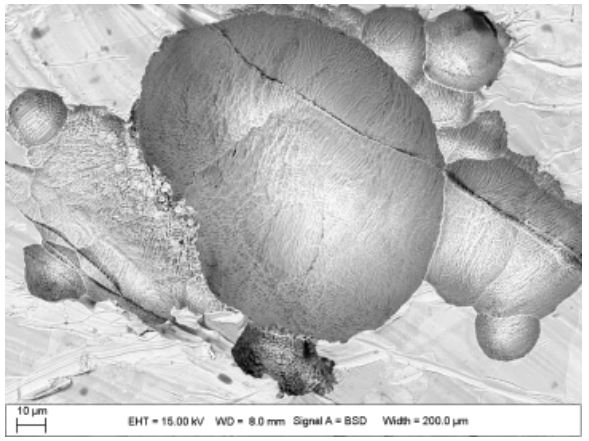
ProX 200
As-printed



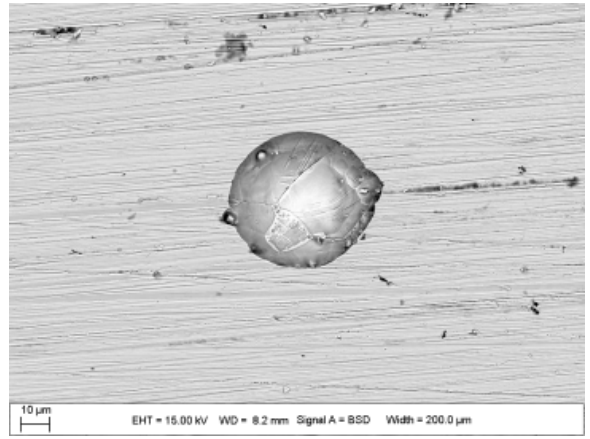

ProX 200
Electropolish



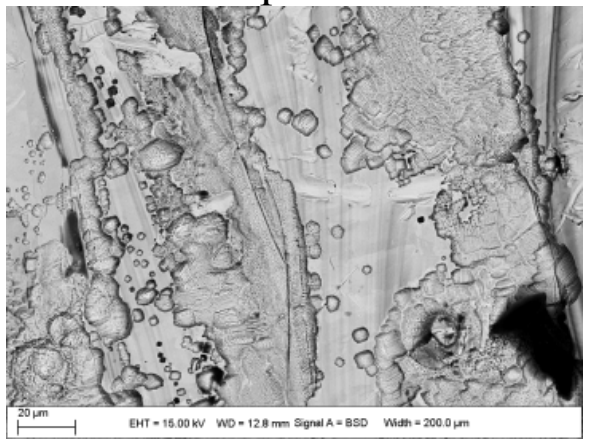

EOS M290
As-printed



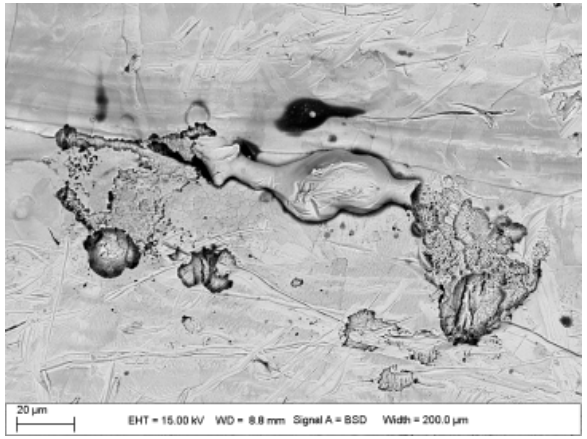

Wrought surface
was polished



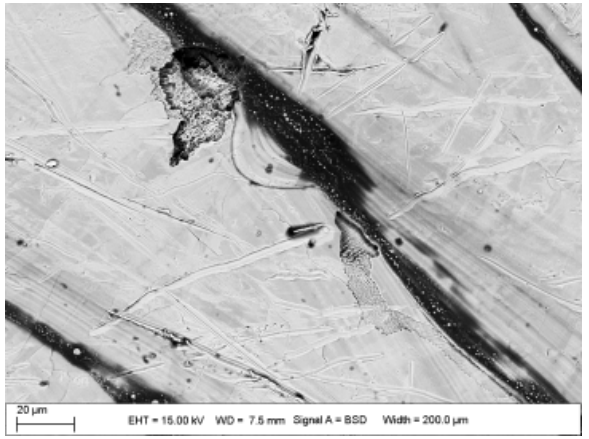

Renishaw
As-printed




Concept M2
As-printed




SLM®280
As-printed




Courtesy of Luis Jauregui (SNL)

# ASTM G85-A2 conclusions (so far)

- Wire EDM as-cut surface had the most aggressive corrosion based on optical analysis.
- Electropolished surfaces were least susceptible to corrosion.
- As-printed samples had different quantities of corrosion based on optical, but similar morphology (many pits appeared to initiate from melt pool boundaries).

***Current results correlate well with electrochemical experiments (breakdown potential, etc.).***

# Thank you for your attention!

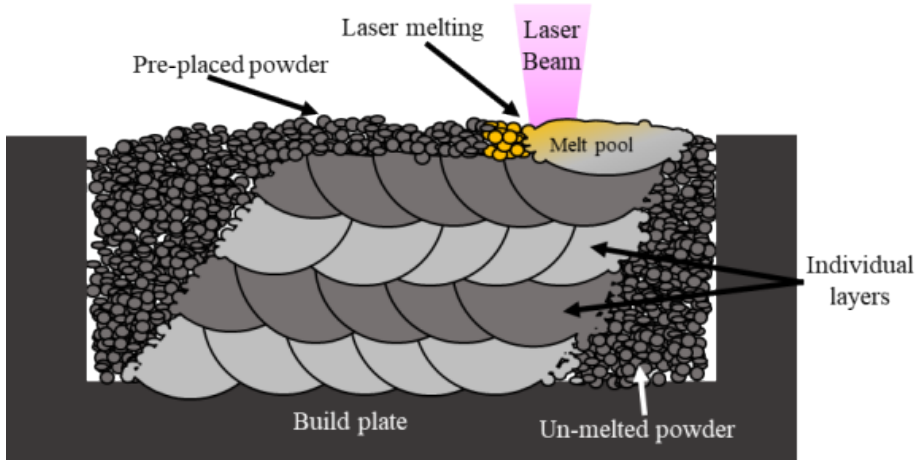
Questions…?

Please contact with questions/comments:

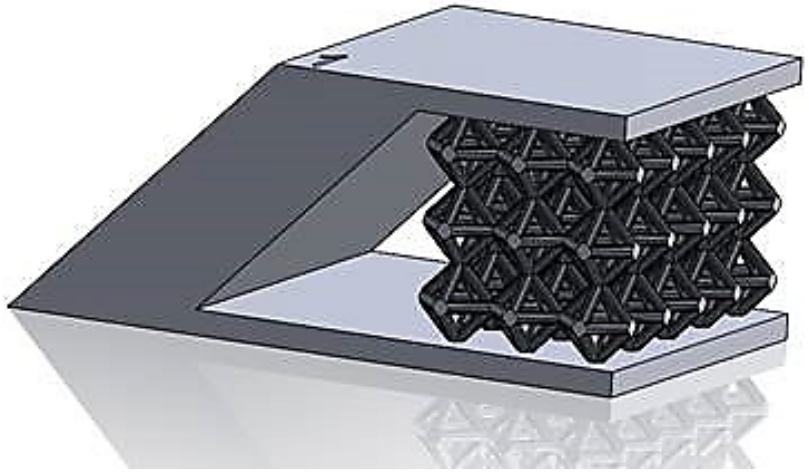
Michael Melia

mamelia@sandia.gov

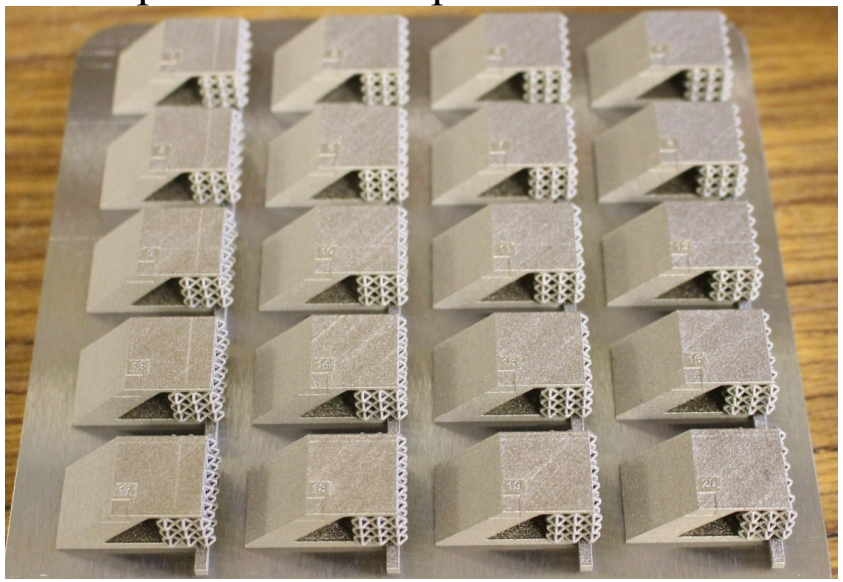
# Powder bed fusion 316L samples




Samples were prepared using 316L powder with a powder bed fusion (PBF) technique.



Build plate of 20 samples

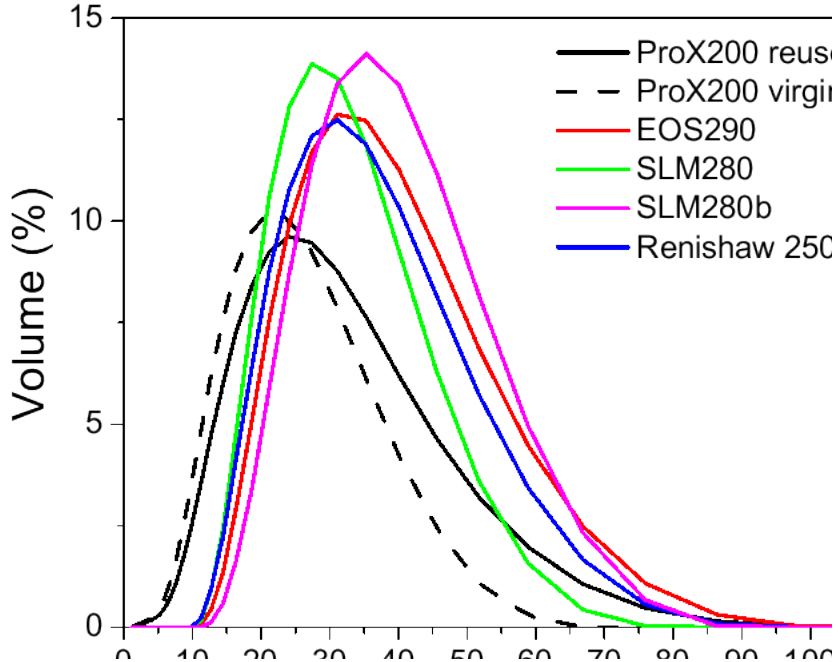


| Machine model number | Power (W) | Scanning velocity (mm/s) | VED (J/mm) | Hatch spacing (um) | Layer thickness (um) | Scan pattern |
|---|---|---|---|---|---|---|
| EOS M290 | 214.2 | 928.1 | 57.7 | 100 | 40 | Stripes |
| 3D Systems ProX DMP200 | 113 | 1400 | 53.8 | 50 | 30 | Hexagon |
| Renishaw AM250 | 200 | 100 | 363.6 | 110 | 50 | Stripes |
| SLM®280 | 175 | 850 | 57.2 | 120 | 30 | Stripes |
| M2 Series 5 | 300 | 700 | 65.9 | 130 | 50 | Stripes |

# Powder characterization

- SEM images of powder.
- Composition determined by ICP-MS and LECO.
- Powder analysis with laser diffraction.

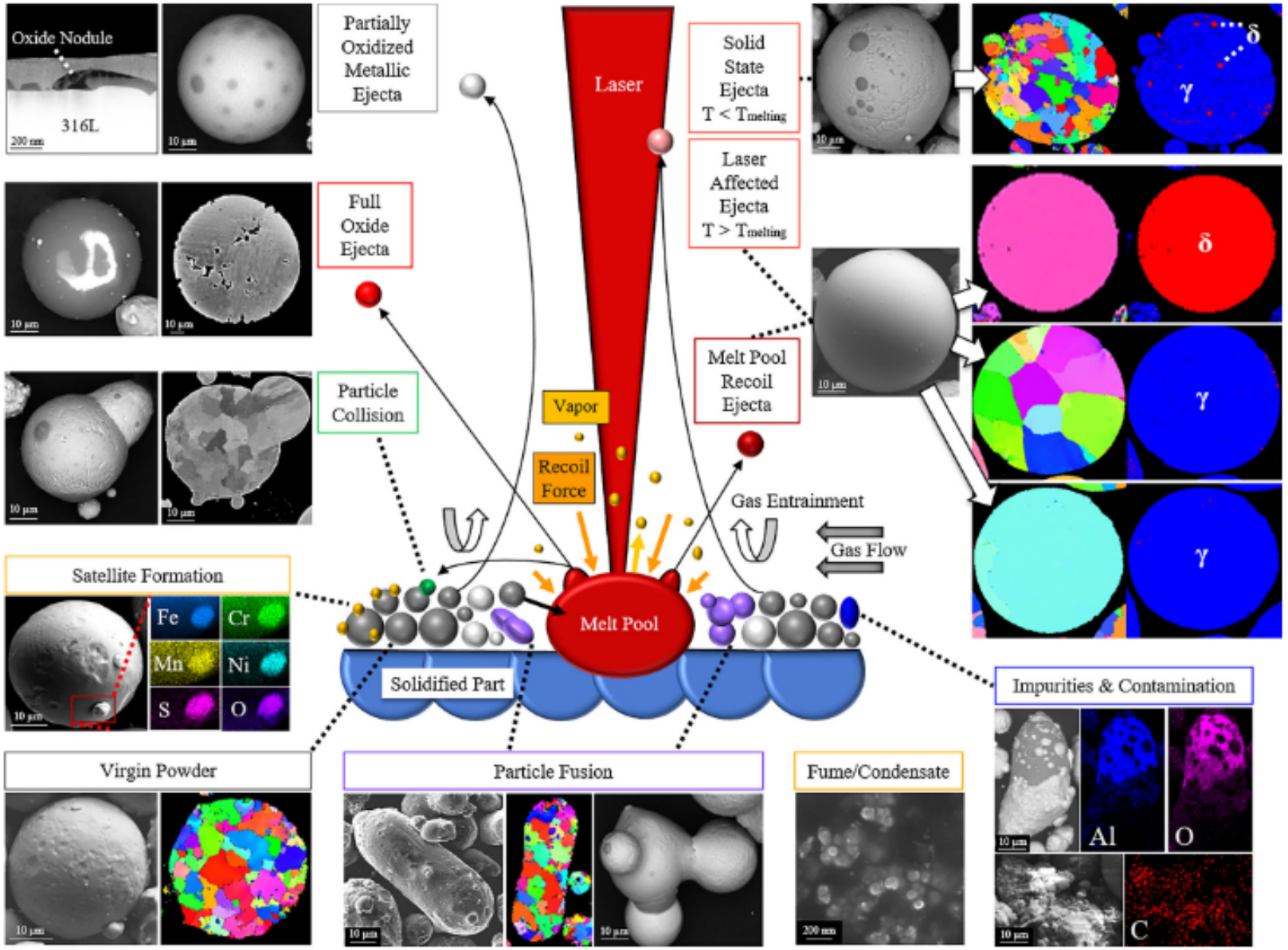
| | ProX 200 reused | EOS M290 reused | SLM280 reused | M2 Series 5 Reused | Renishaw reused |
|---|---|---|---|---|---|
| Apparent Density (g/cc) | 4.25 | 4.22 | 3.97 | 4.16 | 4.26 |
| ASTM B964 Carney Flow (sec./150 g.) | 13 | 9 | 9 | 8 | 8 |
| Hall Flow ASTM B213 (sec./50 g.) | 17 | 13 | 14 | 12 | 13 |
| Skeletal Density (g/cc) | 7.9893 | 7.9549 | 7.9891 | 7.9234 | 7.9552 |
| Tap Density (g/cc) | 5.07 | 5.02 | 4.94 | 5.02 | 5.14 |




| Wt% | Al | C | Cr | Cu | Fe | Mn | Mo | N | Ni | O | P | S | Si |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ProX 200 | 0.003 | 0.018 | 17.12 | 0.15 | 67.2 | 1.28 | 2.19 | 0.12 | 11.18 | 0.11 | 0.015 | 0.013 | 0.49 |
| EOS M290 | 0.003 | 0.024 | 17.8 | 0.013 | 65.5 | 0.77 | 2.19 | 0.099 | 12.96 | 0.032 | 0.005 | 0.006 | 0.57 |
| SLM®280 | 0.006 | 0.012 | 16.83 | 0.11 | 67.6 | 1.18 | 2.24 | 0.059 | 11.33 | 0.055 | 0.008 | 0.009 | 0.43 |
| M2 Series 5 | 0.007 | 0.028 | 17.7 | 0.026 | 65.8 | 0.53 | 2.24 | 0.071 | 12.87 | 0.03 | 0.005 | 0.008 | 0.55 |
| Renishaw | 0.005 | 0.025 | 17.12 | 0.013 | 66.6 | 1.08 | 2.33 | 0.031 | 12.13 | 0.049 | 0.005 | 0.007 | 0.47 |

Courtesy of NSL Analytical

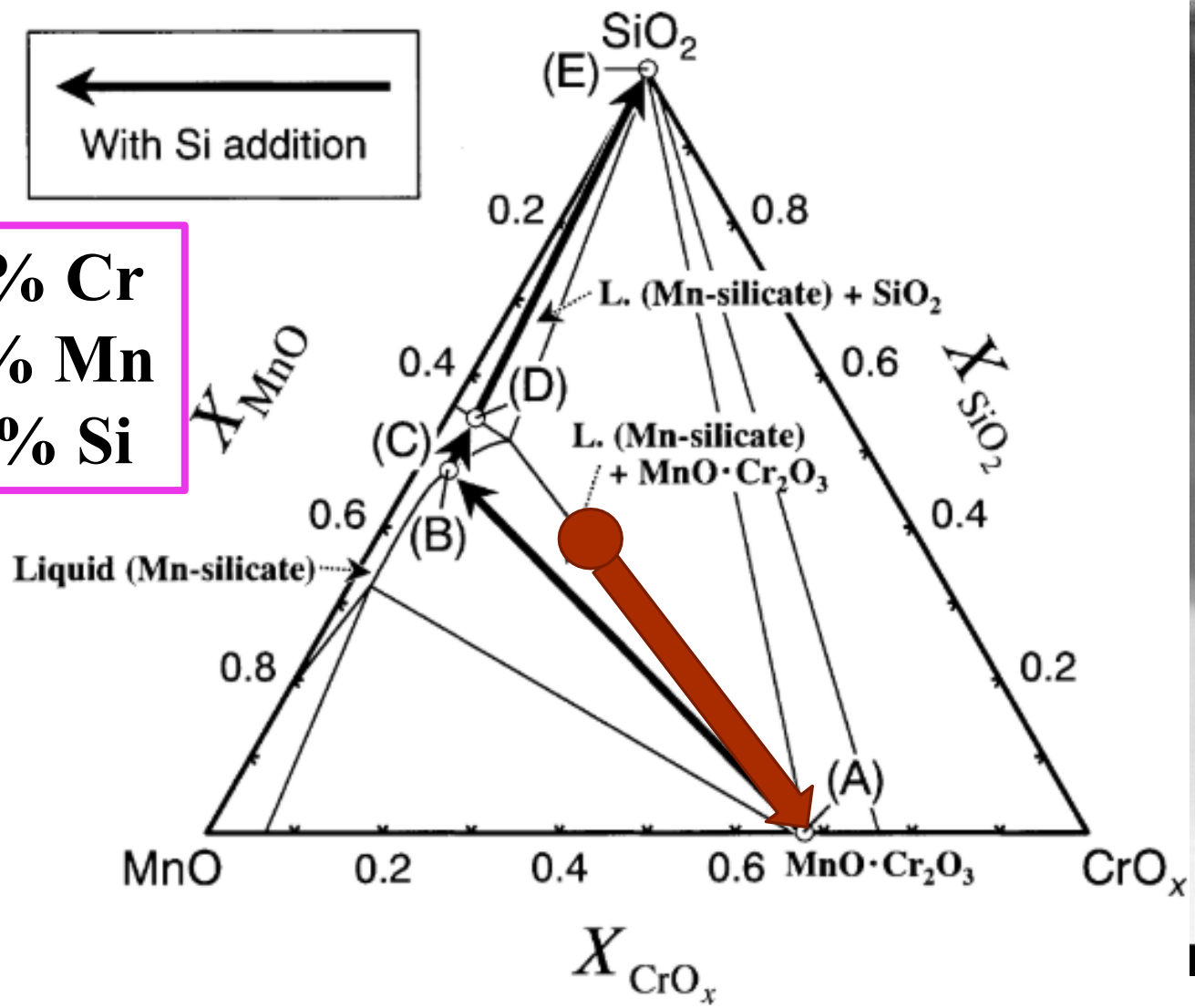
# Mechanism for the oxide formation




M.J. Heiden, et al., Addit. Manuf., (2019)

(UUR)

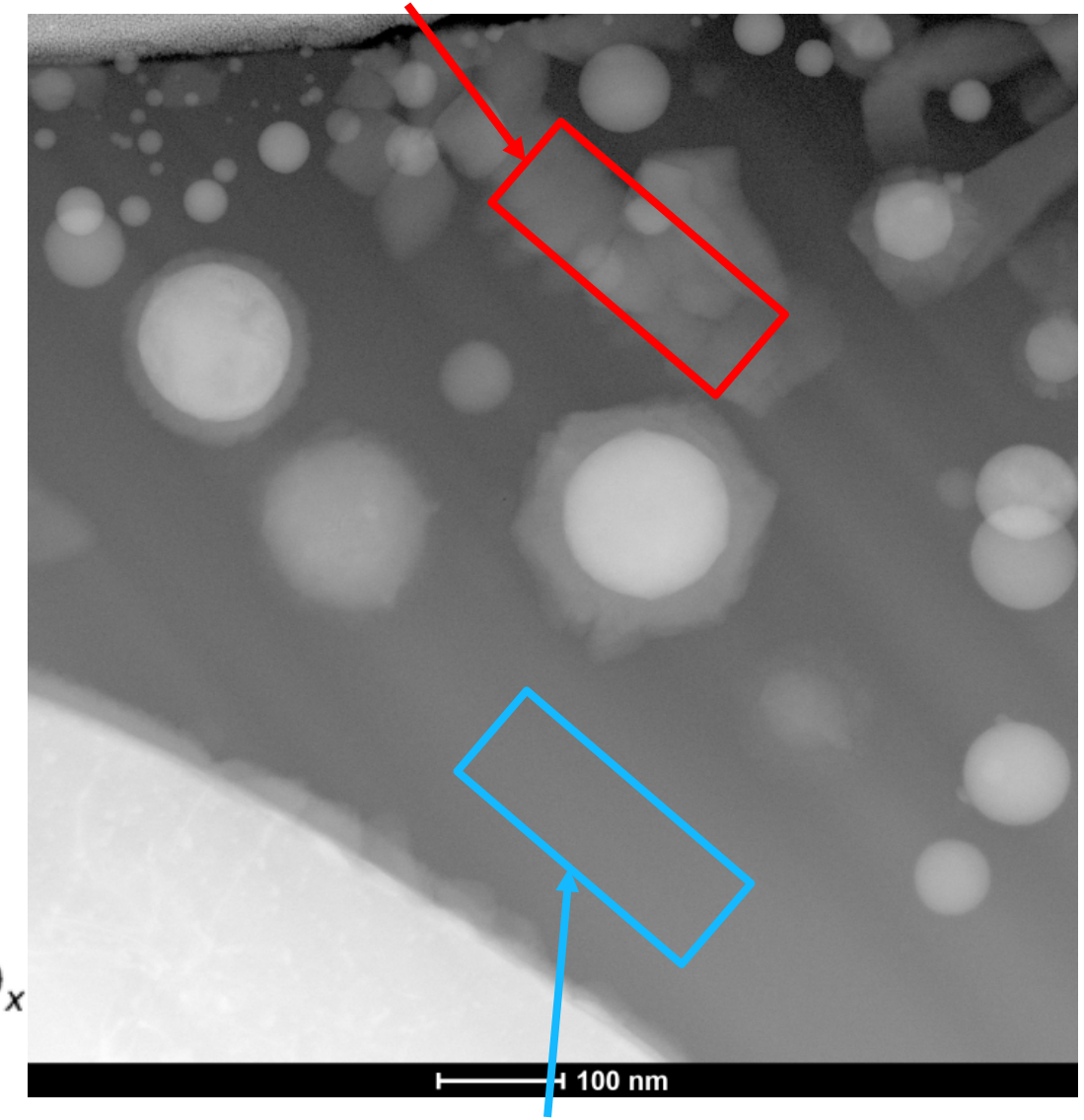
# How and why do these oxides form?




M. Tanahashi, et al., Phase Equilibria of the MnO, $SiO_2$, $CrO_x$ System at 1873 K under Controlled Oxygen Partial Pressure, ISIJ Int., (2001).

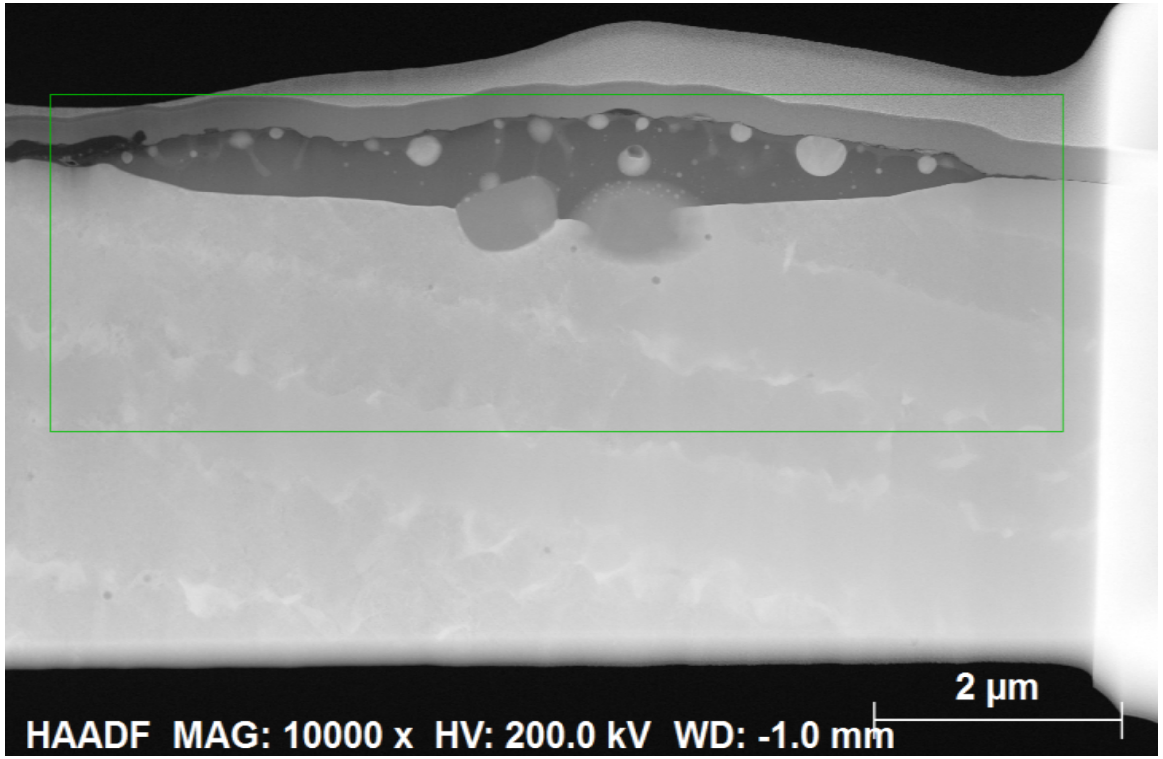
(UUR)

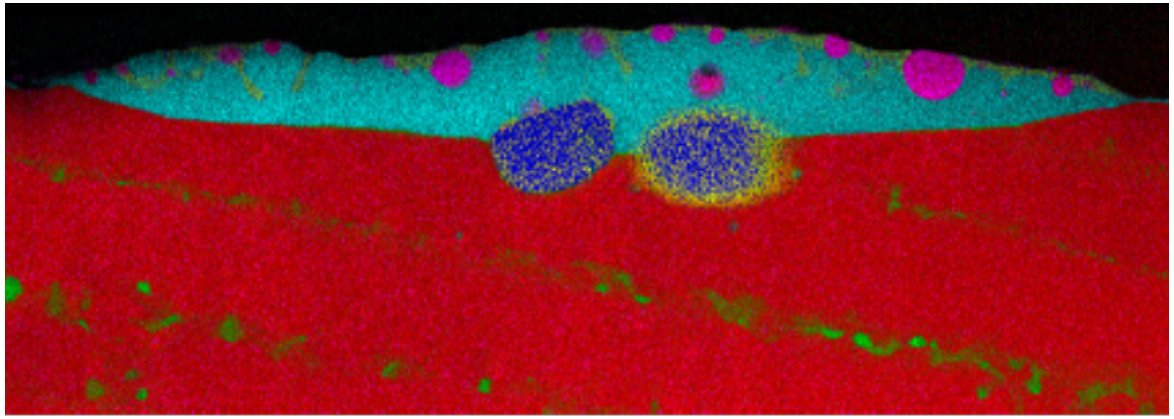
## 70% Cr-30% Mn oxide




## 23% Cr-38% Mn-36% Si-3% Al

# Oxides on Inconel 718 surface from SLM280



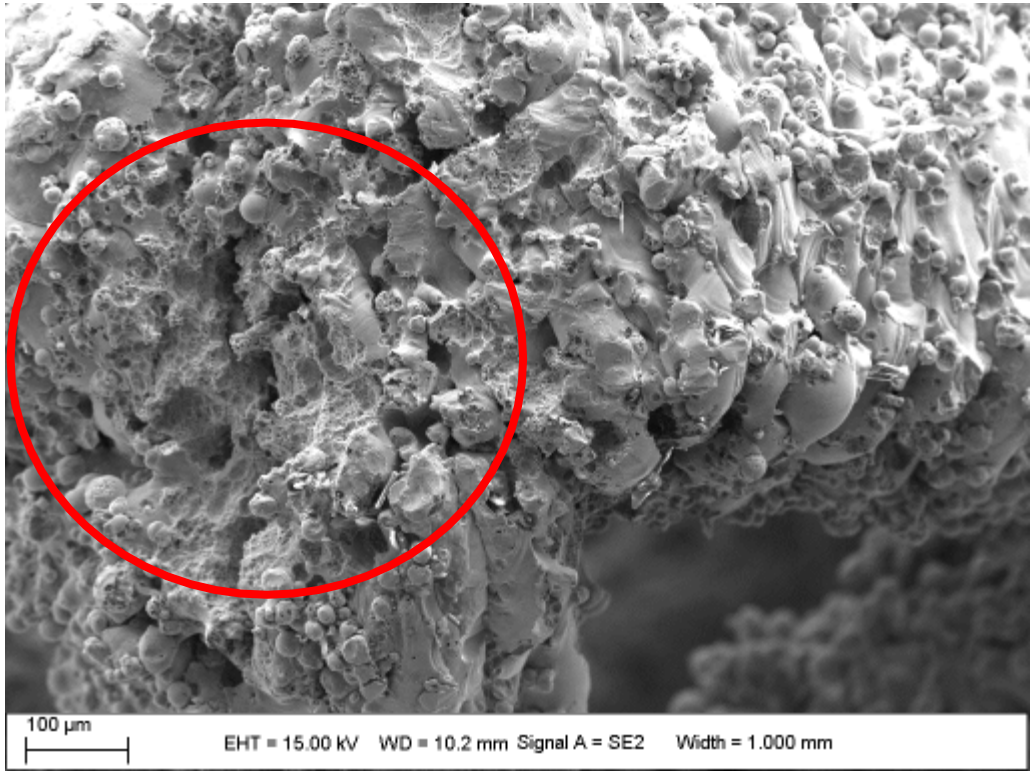



Red = Ni, Cr, Fe, Nb, Mo, Ti
Green = Nb, Ti enriched
Blue = Ti, Nb
***Cyan = Al, Ti, O***
Magenta = Cr, Ni, Fe, Ti
Yellow = Ti, Al, Ni, O

# Pit morphology - Lattices

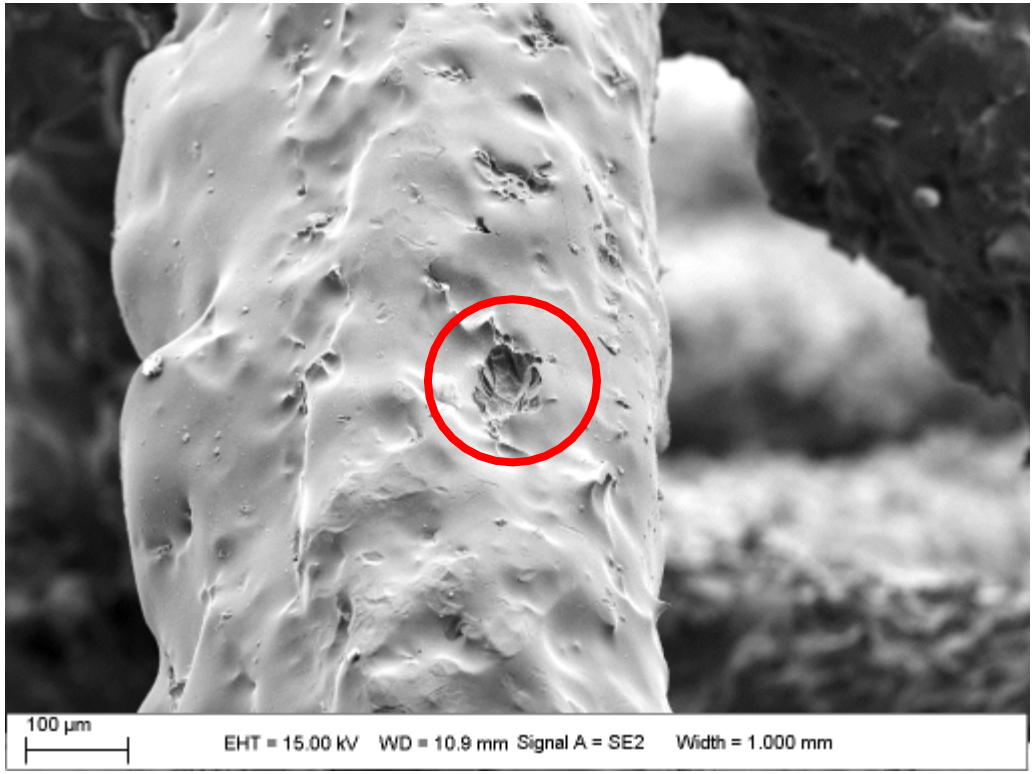
ProX 200

**As-printed**




ProX 200

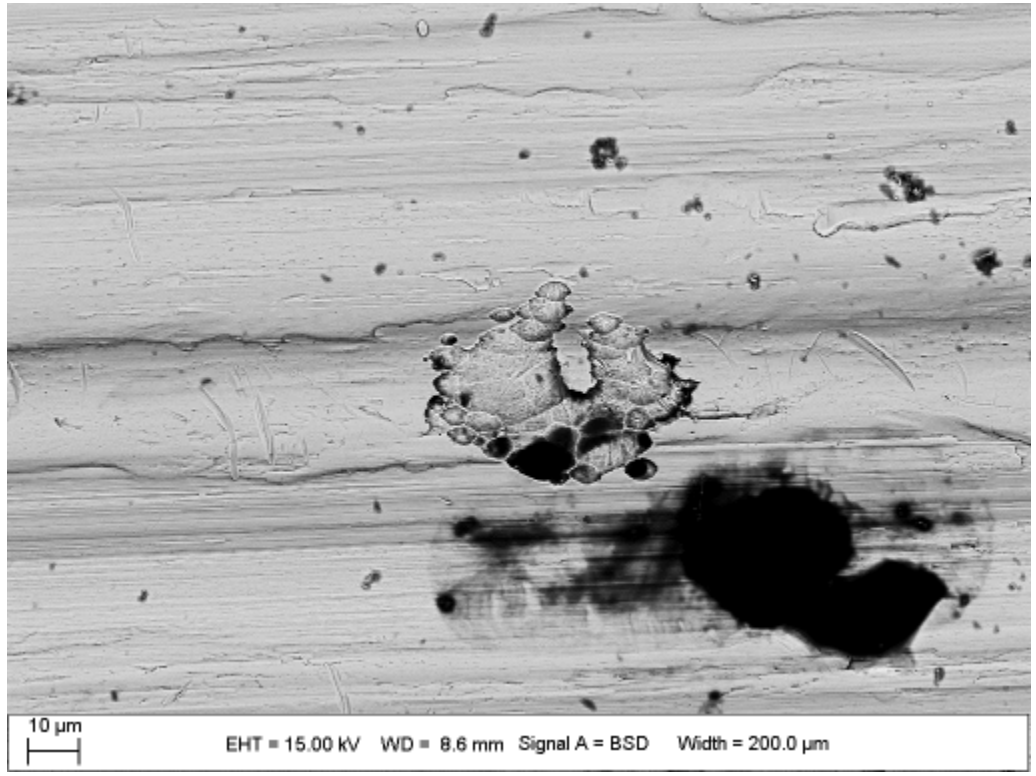
**Electropolish**



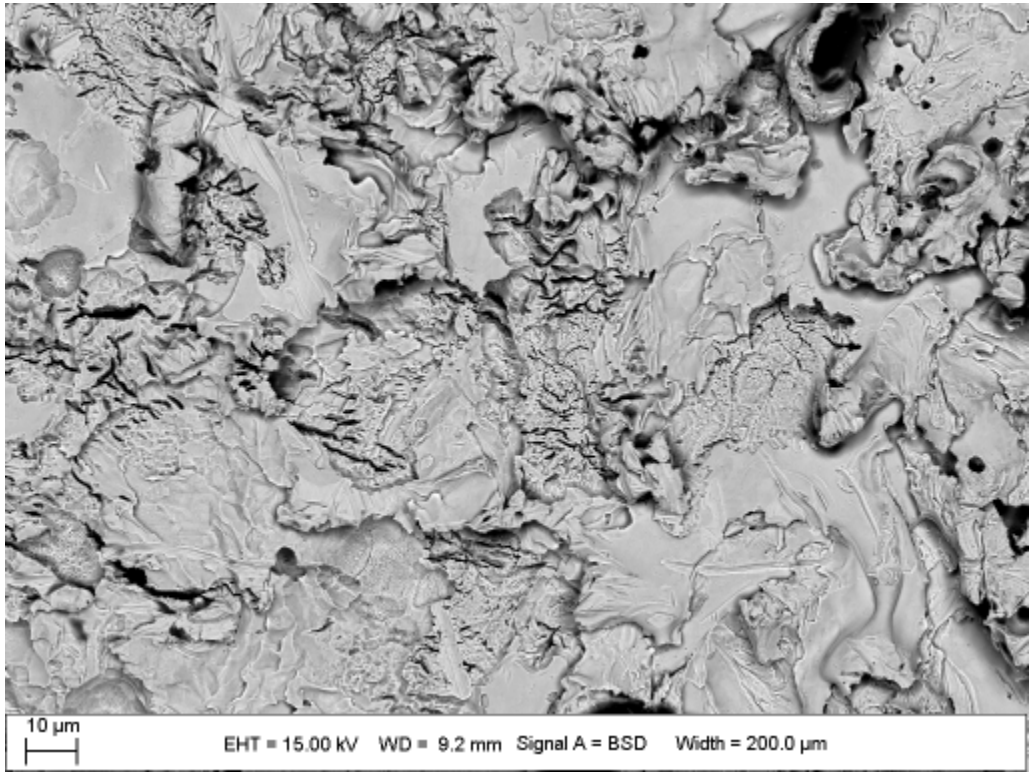

Courtesy of Luis Jauregui (SNL)

# Pit morphology

## Bandsaw cut surface



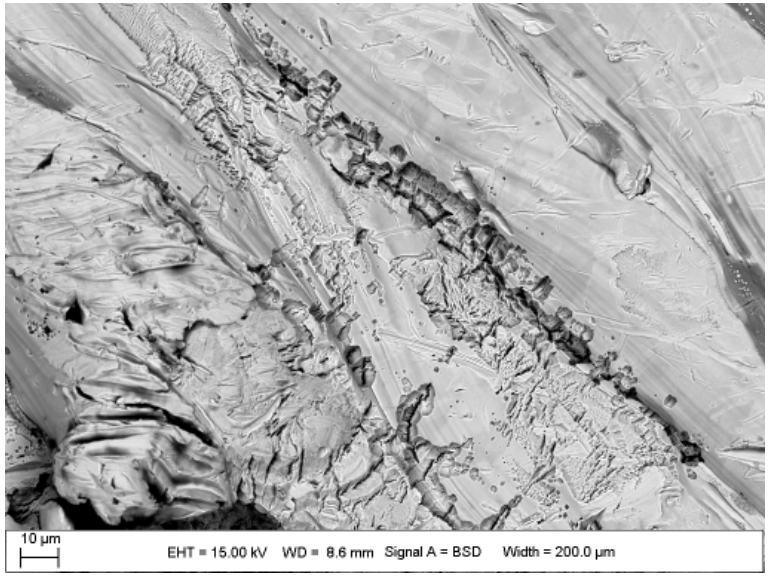

## Wire EDM cut surface



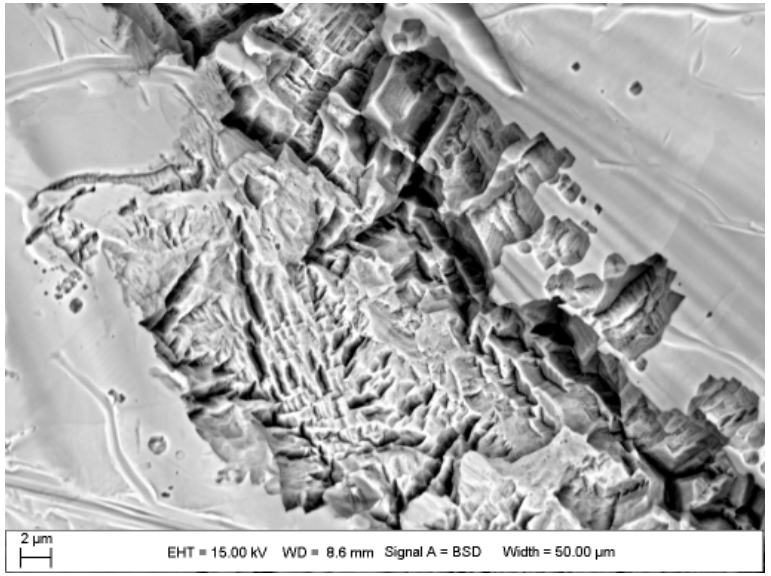

(UUR) Courtesy of Luis Jauregui (SNL)

# Pit morphology

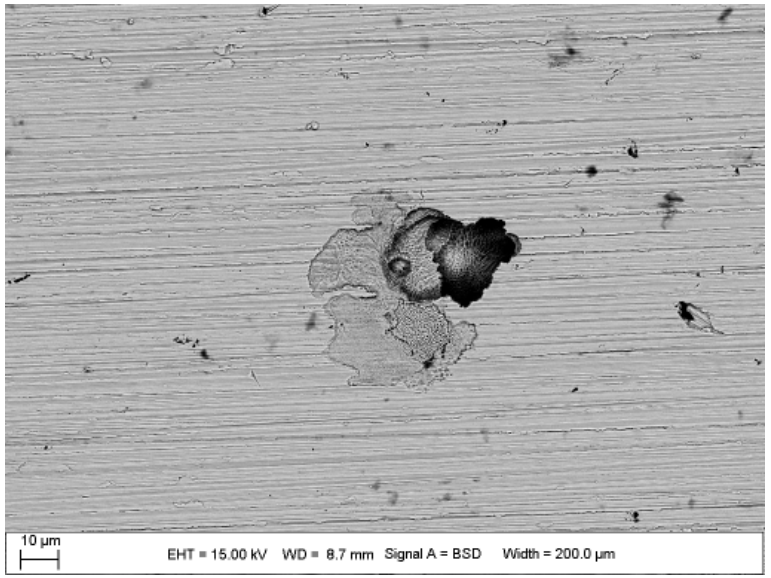
## ProX 200 **As-printed**



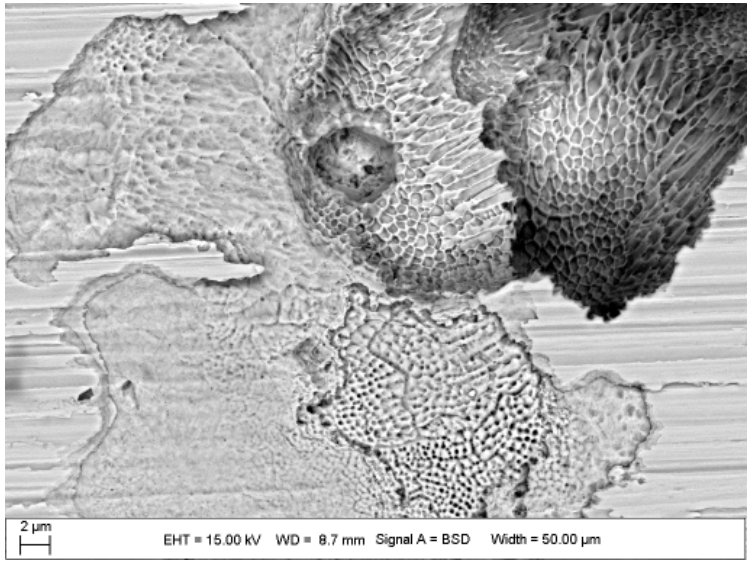

*ASTM G85-A2*




## **PBF316L (Renishaw)**
## surface was polished



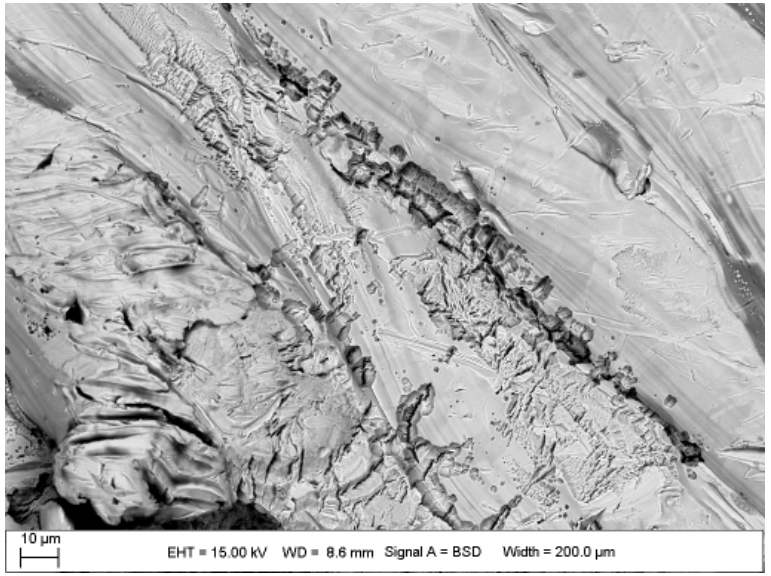

*40% RH - 300 µg/cm² of artificial sea water*




(UUR)

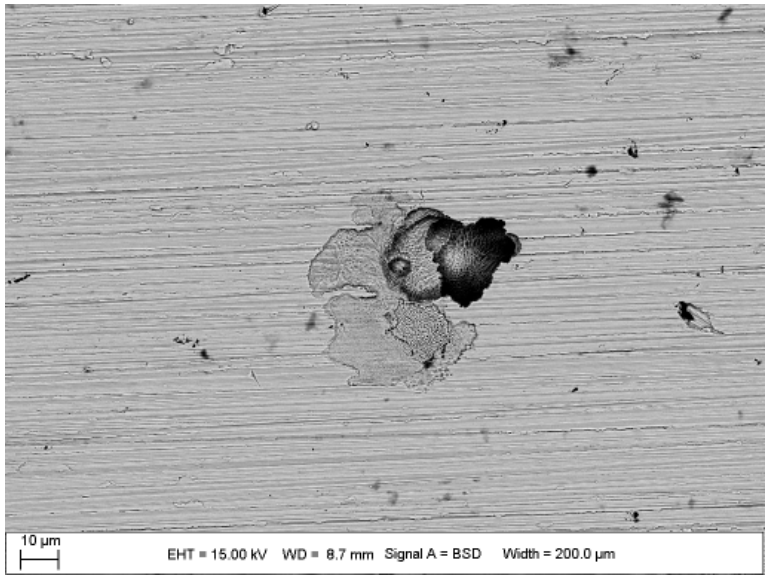
# Pit morphology

## ProX 200 **As-printed**

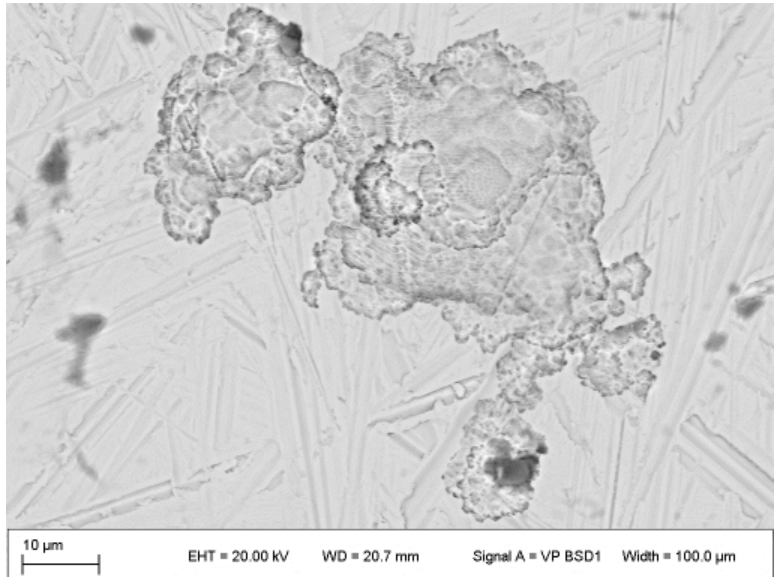



*ASTM G85-A2*

## **PBF316L (Renishaw)**
surface was polished




*40% RH - 300 µg/cm² of artificial sea water*

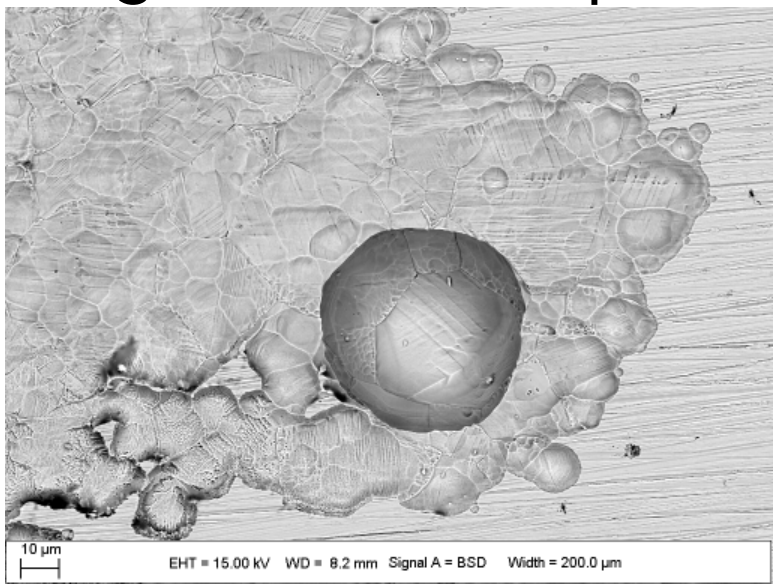



(UUR)

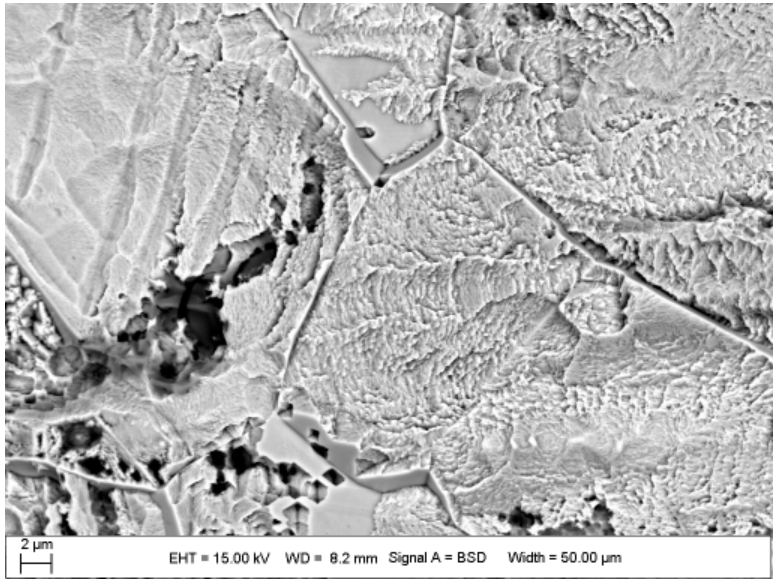
***From 21 month exposure off coast of Florida***

# Pit morphology

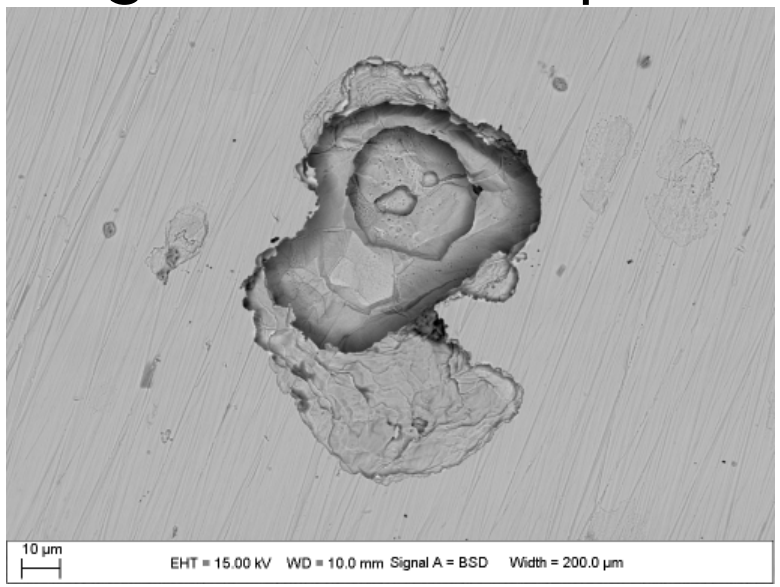
**Wrought** surface was polished



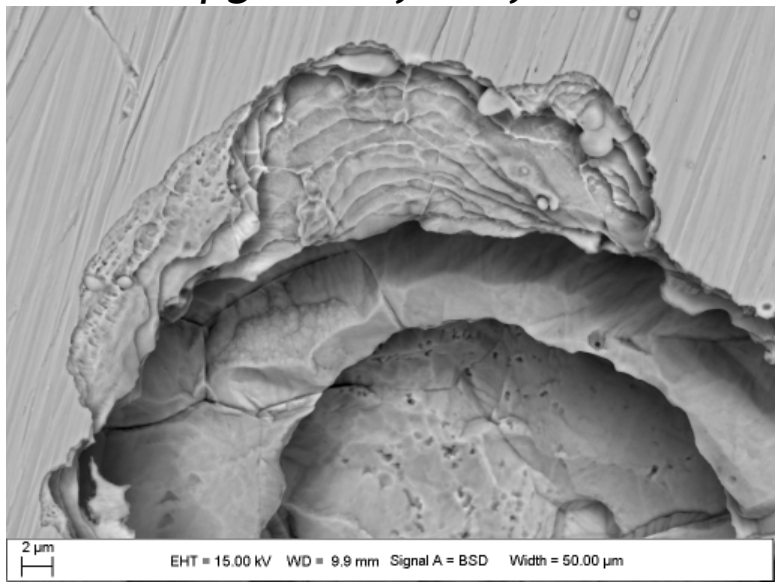

*ASTM G85-A2*




**Wrought** surface was polished



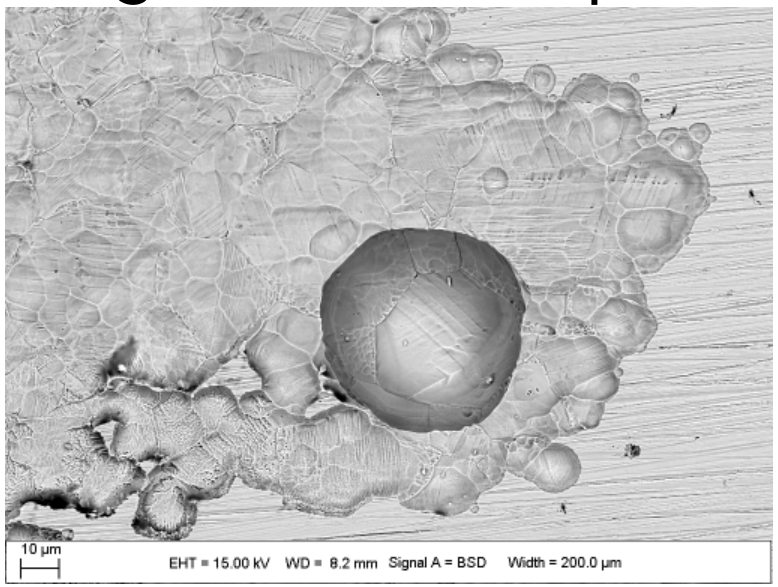

*40% RH - 300 µg/cm² of artificial sea water*




(UUR)

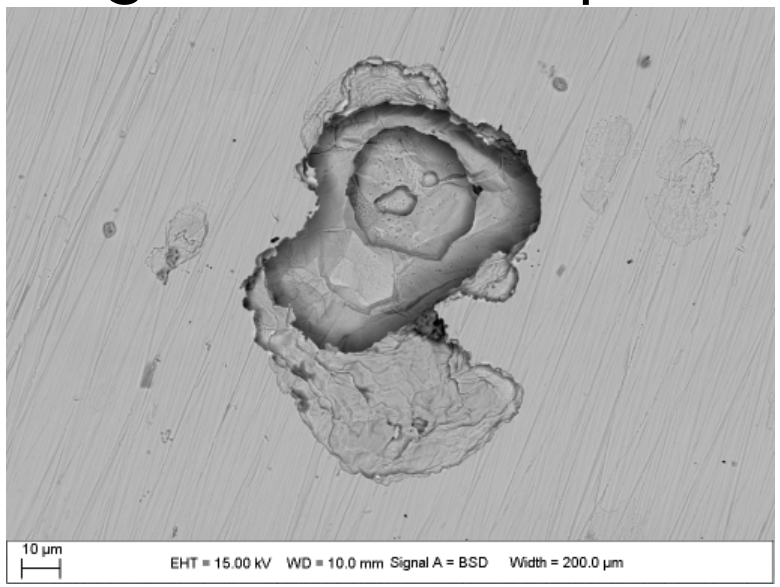
# Pit morphology

**Wrought** surface was polished



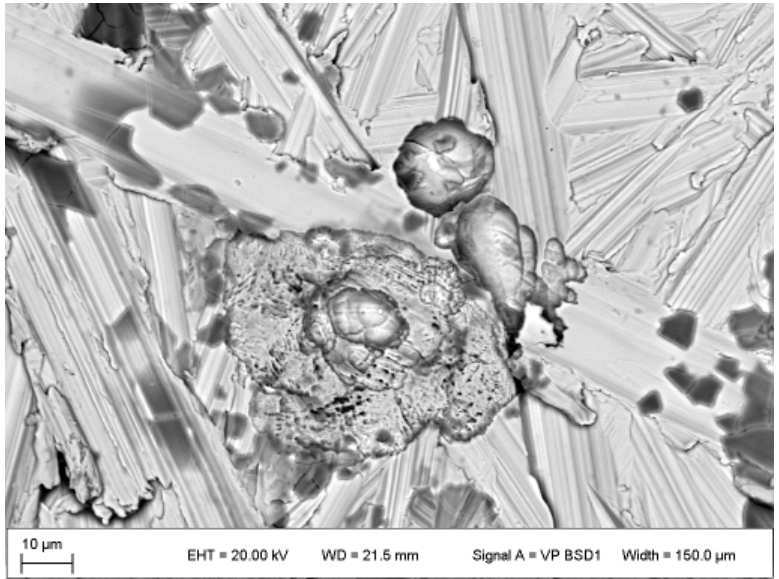

*ASTM G85-A2*

**Wrought** surface was polished



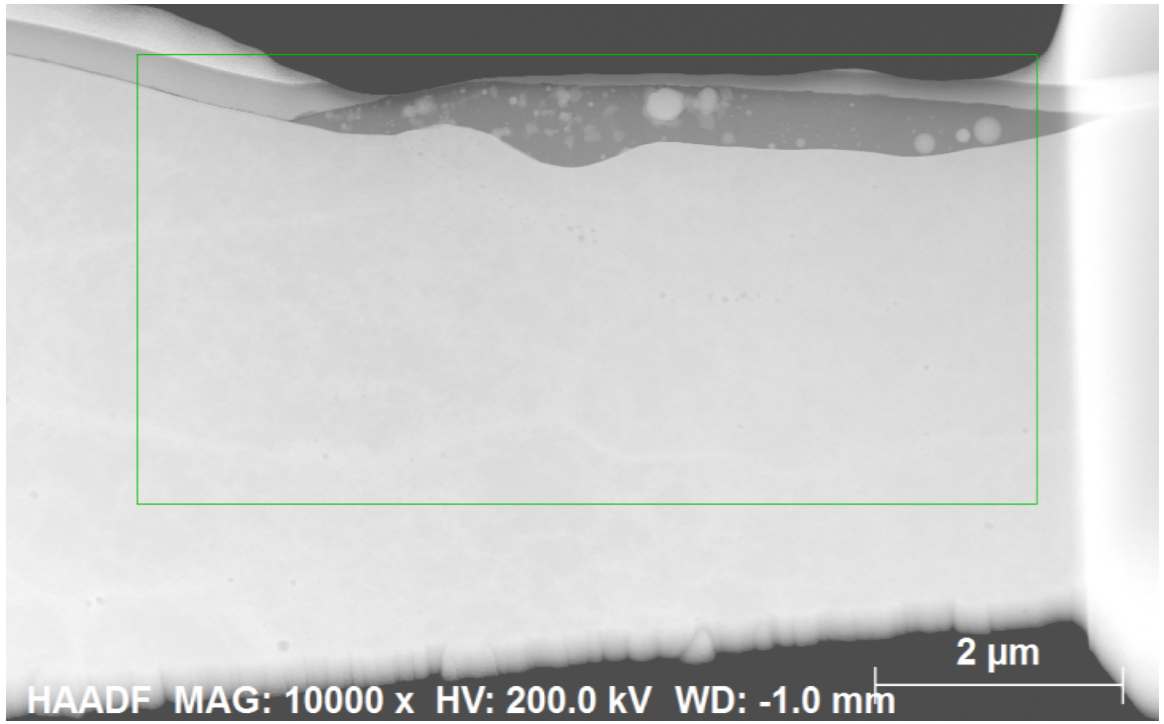

*40% RH - 300 µg/cm² of artificial sea water*

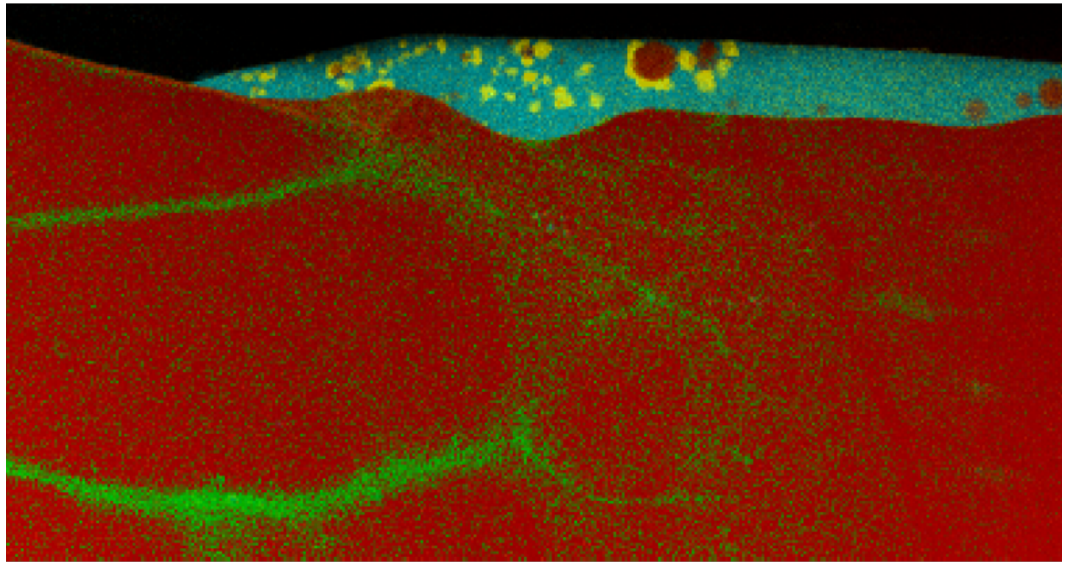
(UUR)




***From 21 month exposure off coast of Florida***

# Oxides on 316L surface from EOS290

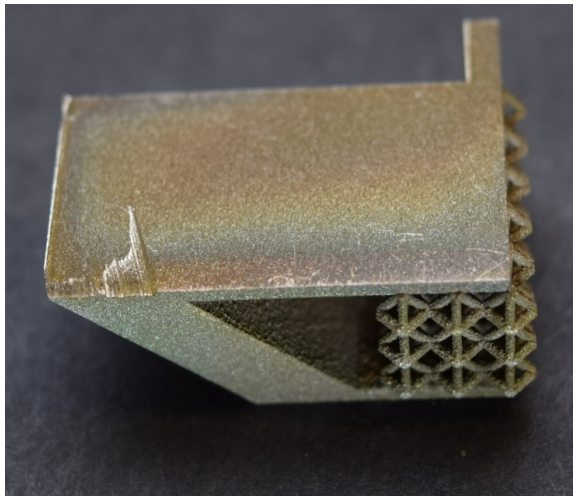


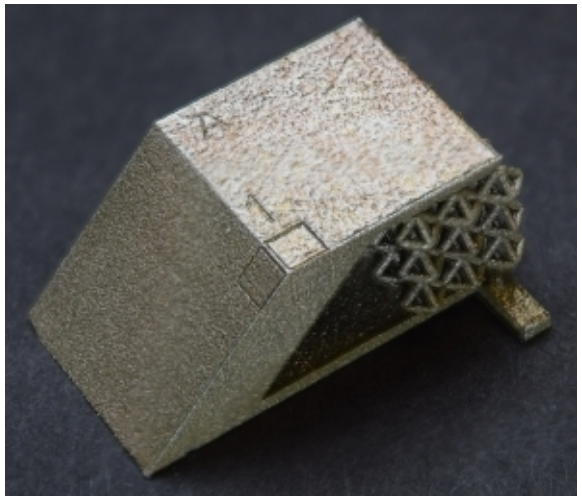
Red = Fe, Cr, Ni, Mn, Mo
Green = Cr, Mo enrichment
***Cyan = Mn, Cr, Ca, Ti, Si, O***
Yellow = Cr, Mn, low Si, Ti, Ca, O

# Wire EDM recast layer from **ProX200**

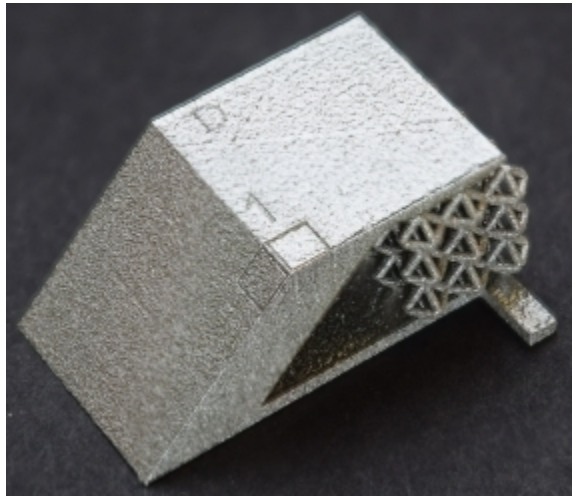
Wire EDM cut surface



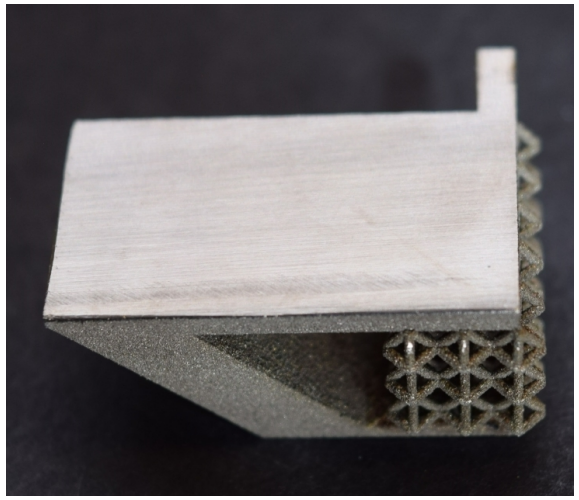
Wire EDM Top view



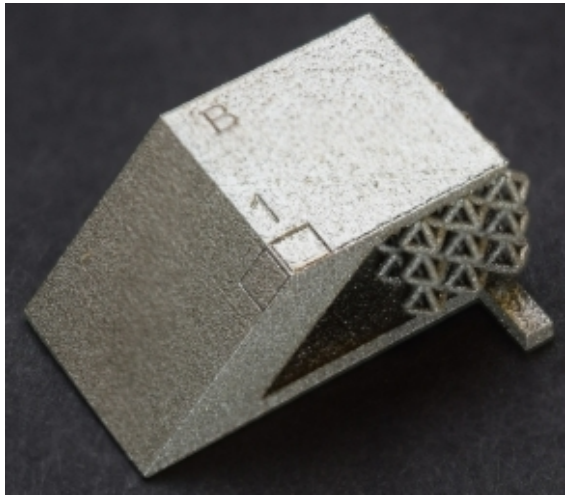

Rustripper Top view



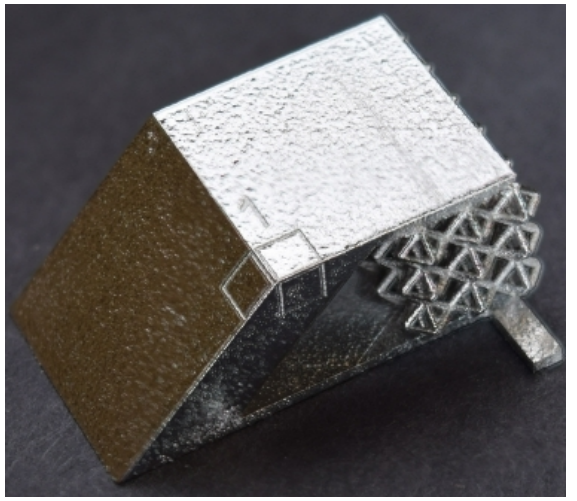

Bandsaw cut surface



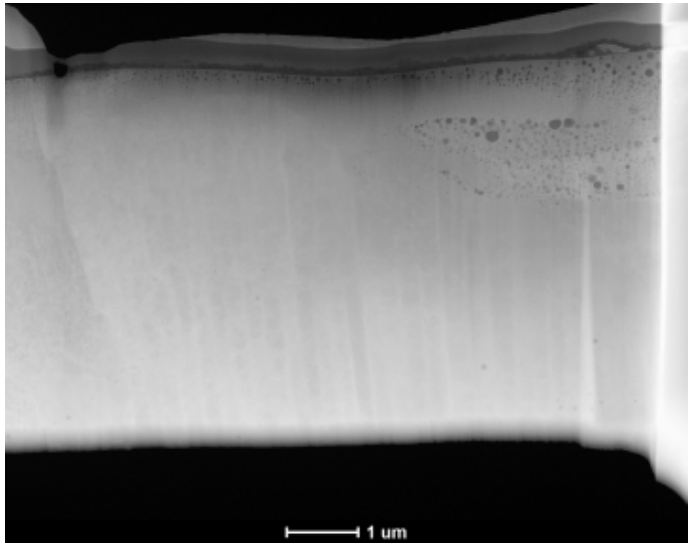
Bandsaw Top view

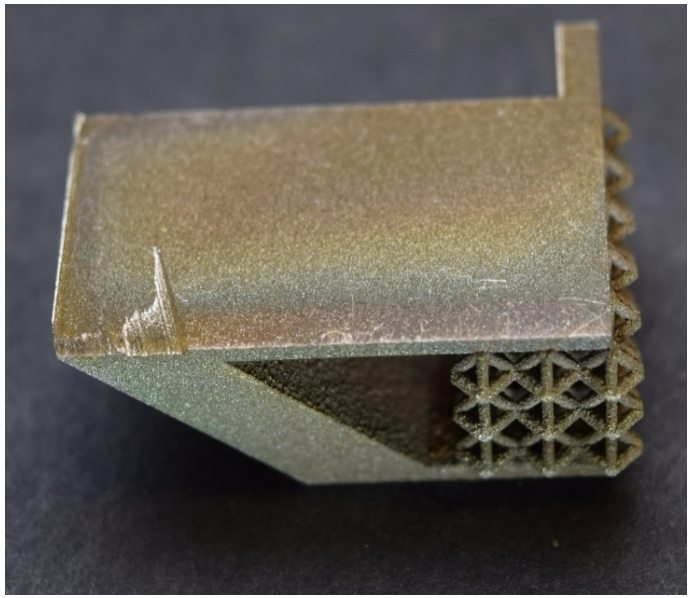


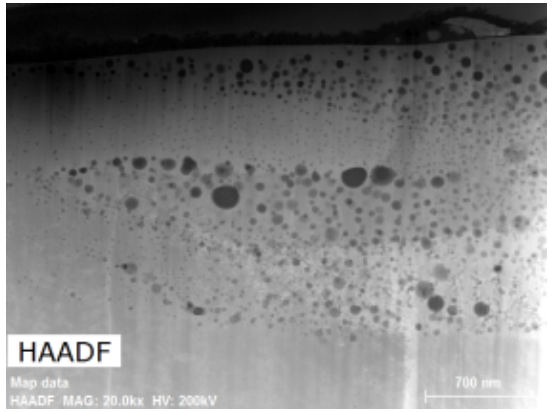

Electropolished Top view

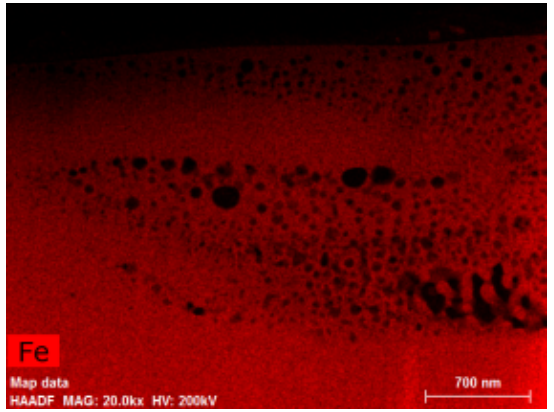


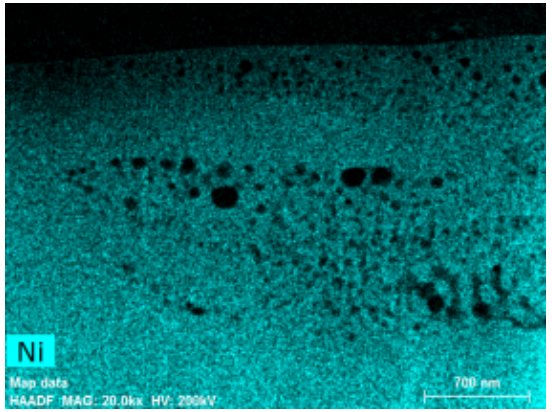
# STEM/EDS of *wire EDM recast layer* from **ProX200**

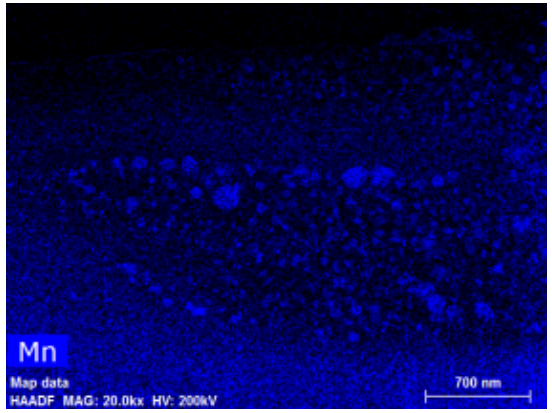


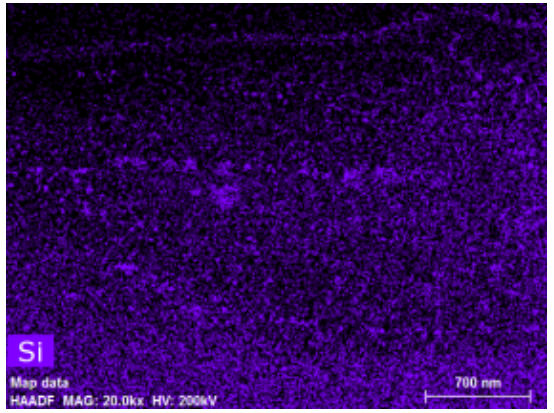



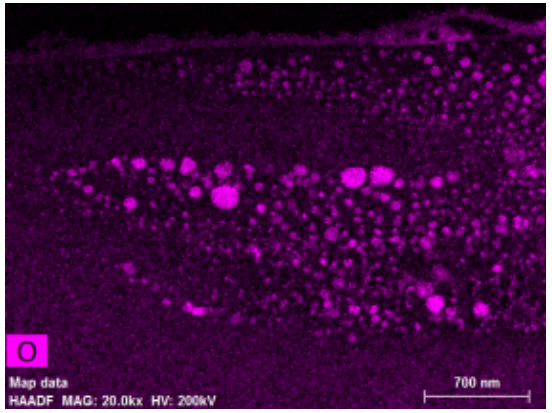


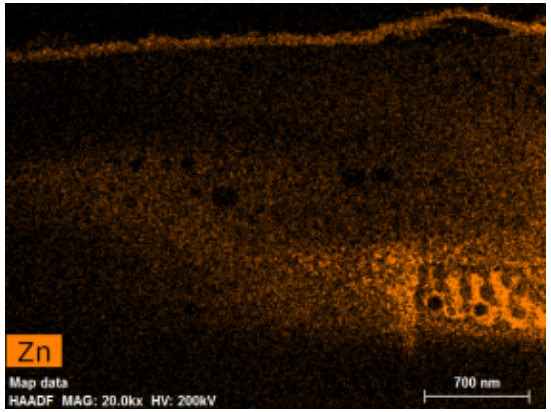



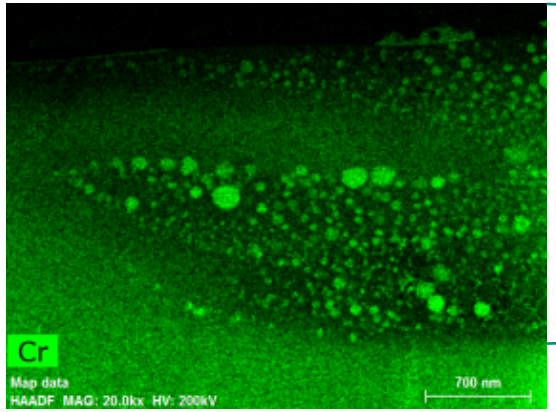




Assuming Cu is in similar area as Zn



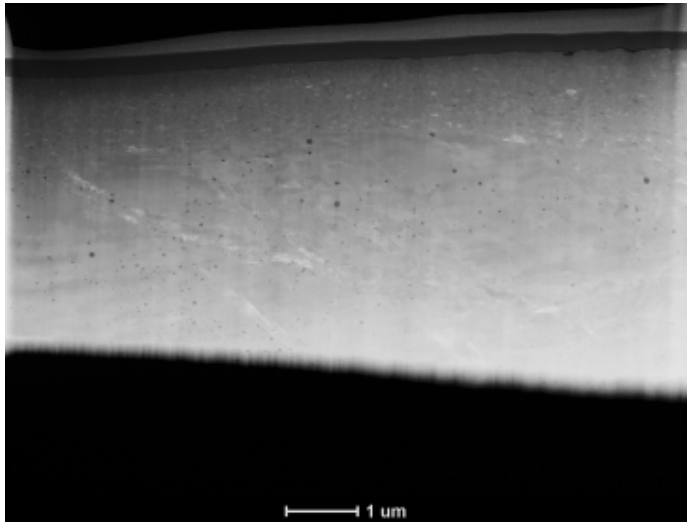



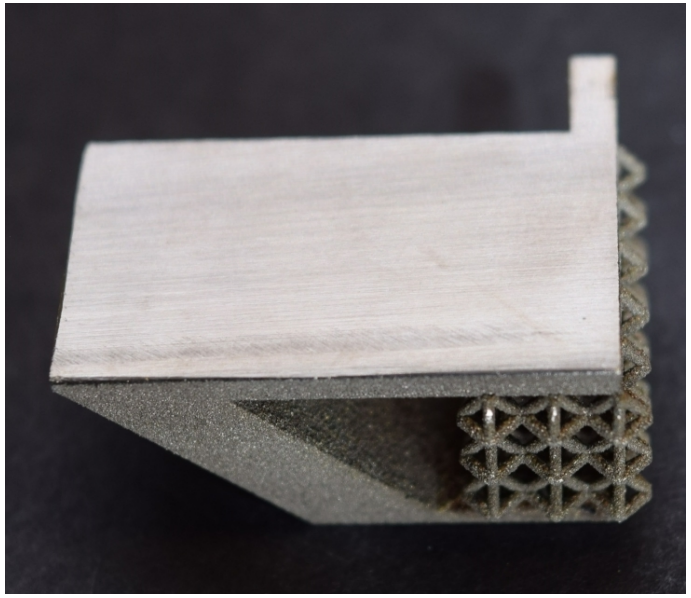

~2 µm thick

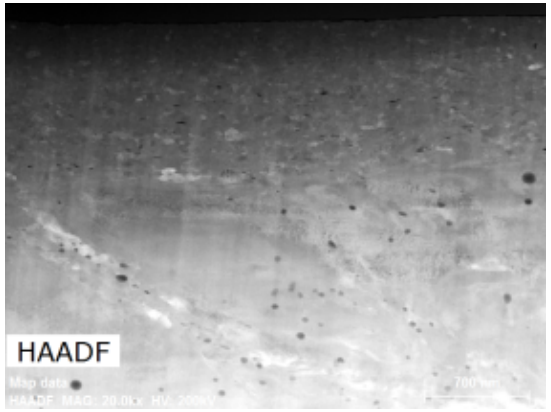
(UUR)

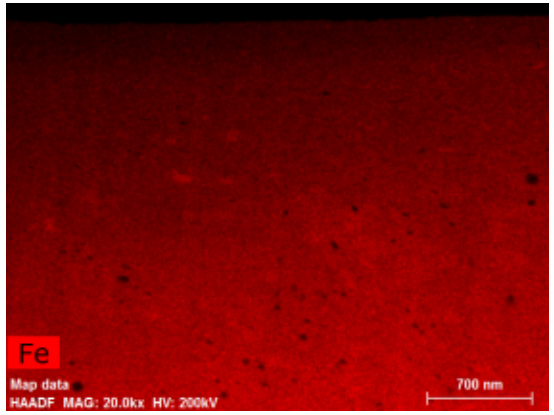
Courtesy: Paul Kotula

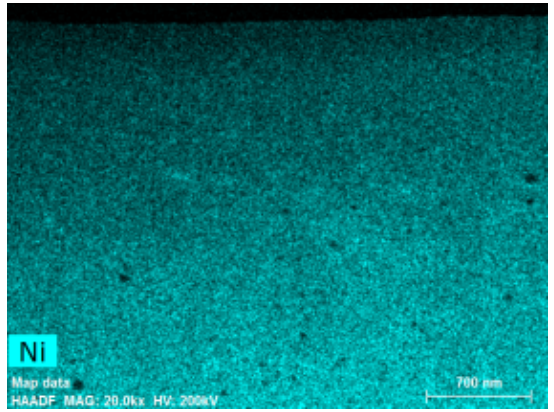
# STEM/EDS of ***Bandsaw deformed layer*** from **ProX200**

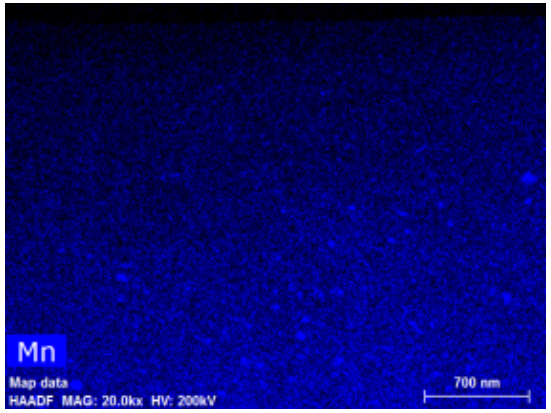


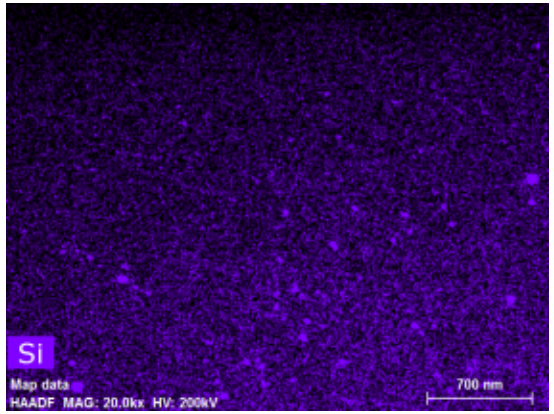



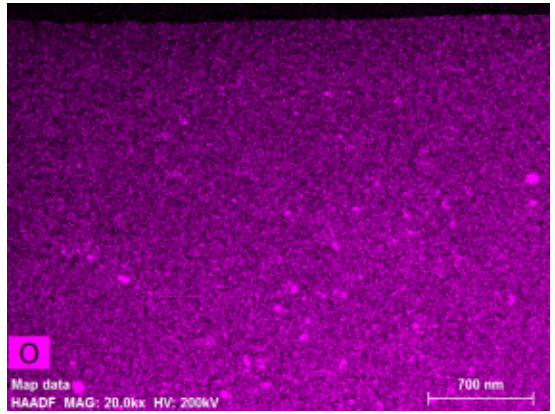


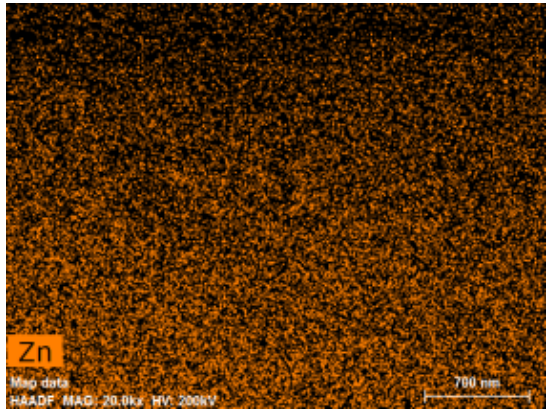



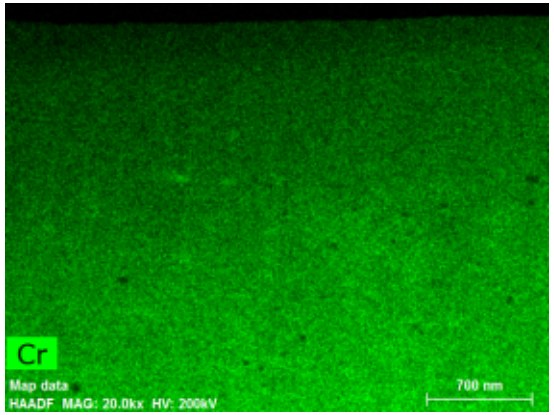




Assuming Cu is in similar area as Zn



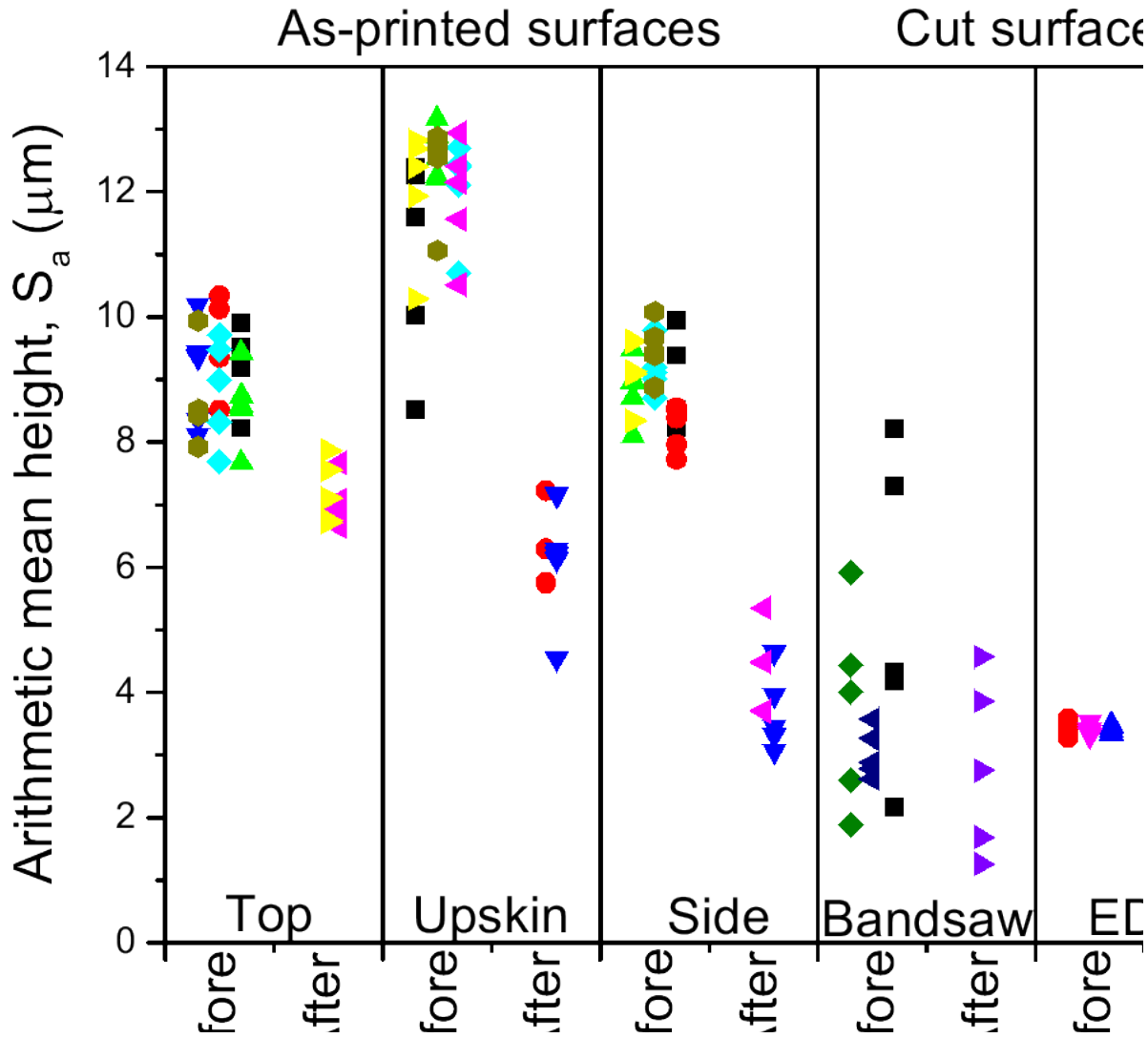




~1.4 µm thick

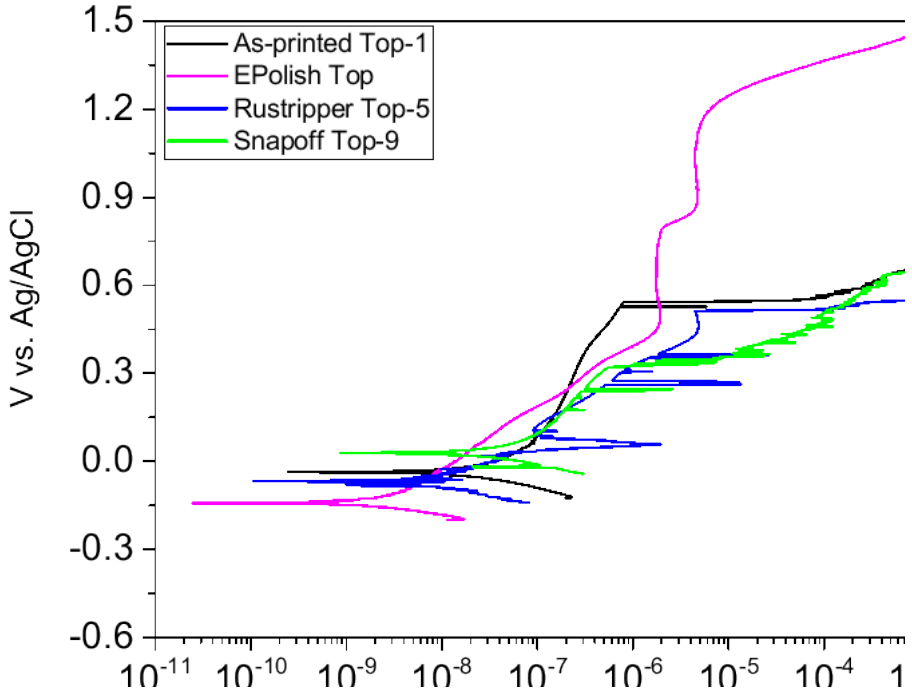
(UUR)

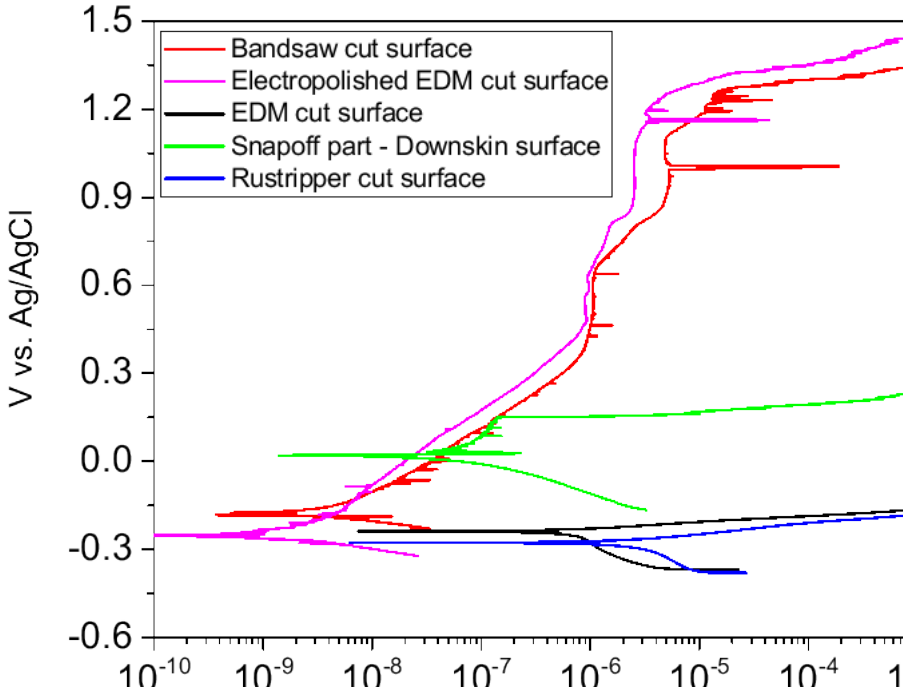
Courtesy: Paul Kotula

# Surface Roughness for **ProX200** Before/After Electropolish



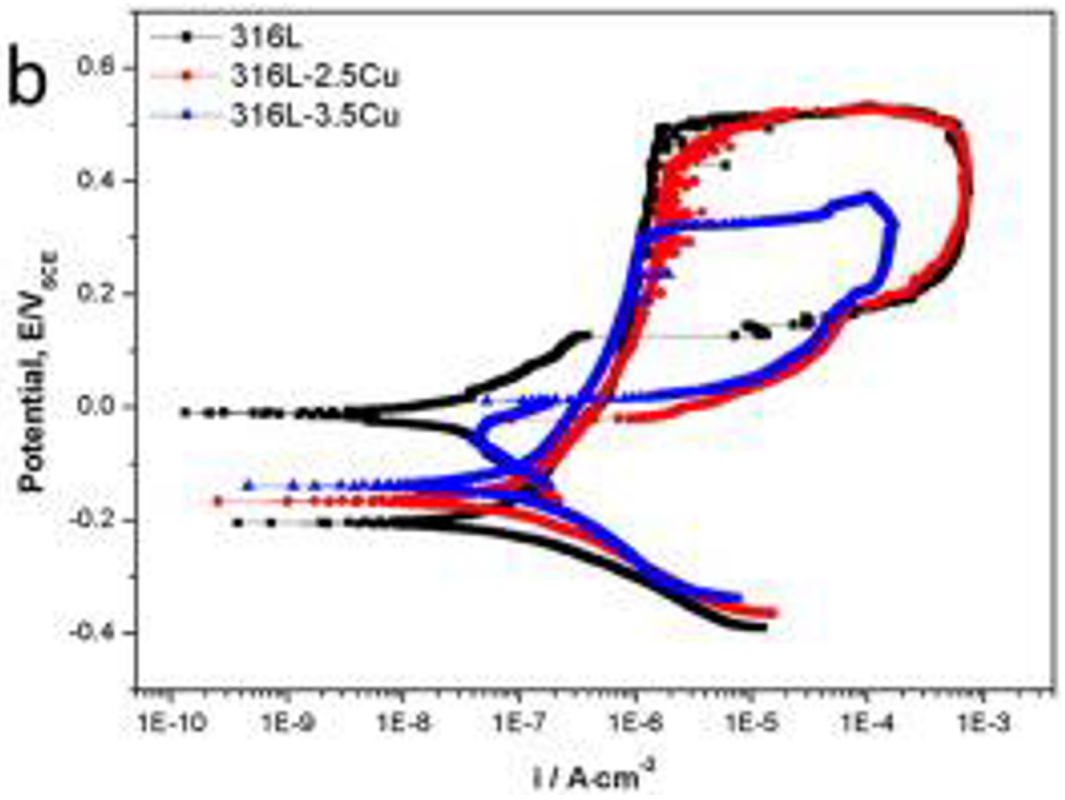

(UUR)


As-printed Top-1
EPolish Top
Rustripper Top-5
Snapoff Top-9
V vs. Ag/AgCl
1.5
1.2
0.9
0.6
0.3
0.0
-0.3
-0.6
10-11 10-10 10-9 10-8 10-7 10-6 10-5 10-4 1

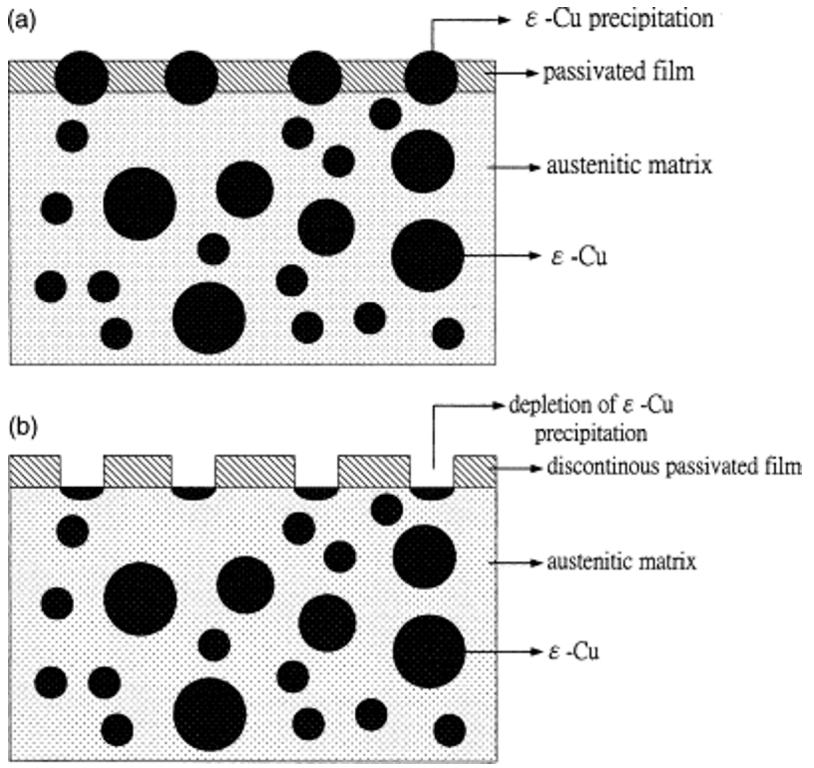

Bandsaw cut surface
Electropolished EDM cut surface
EDM cut surface
Snapoff part - Downskin surface
Rustripper cut surface
V vs. Ag/AgCl
1.5
1.2
0.9
0.6
0.3
0.0
-0.3
-0.6
10-10 10-9 10-8 10-7 10-6 10-5 10-4 1

(UUR)

# Cu additions to steel and corrosion response



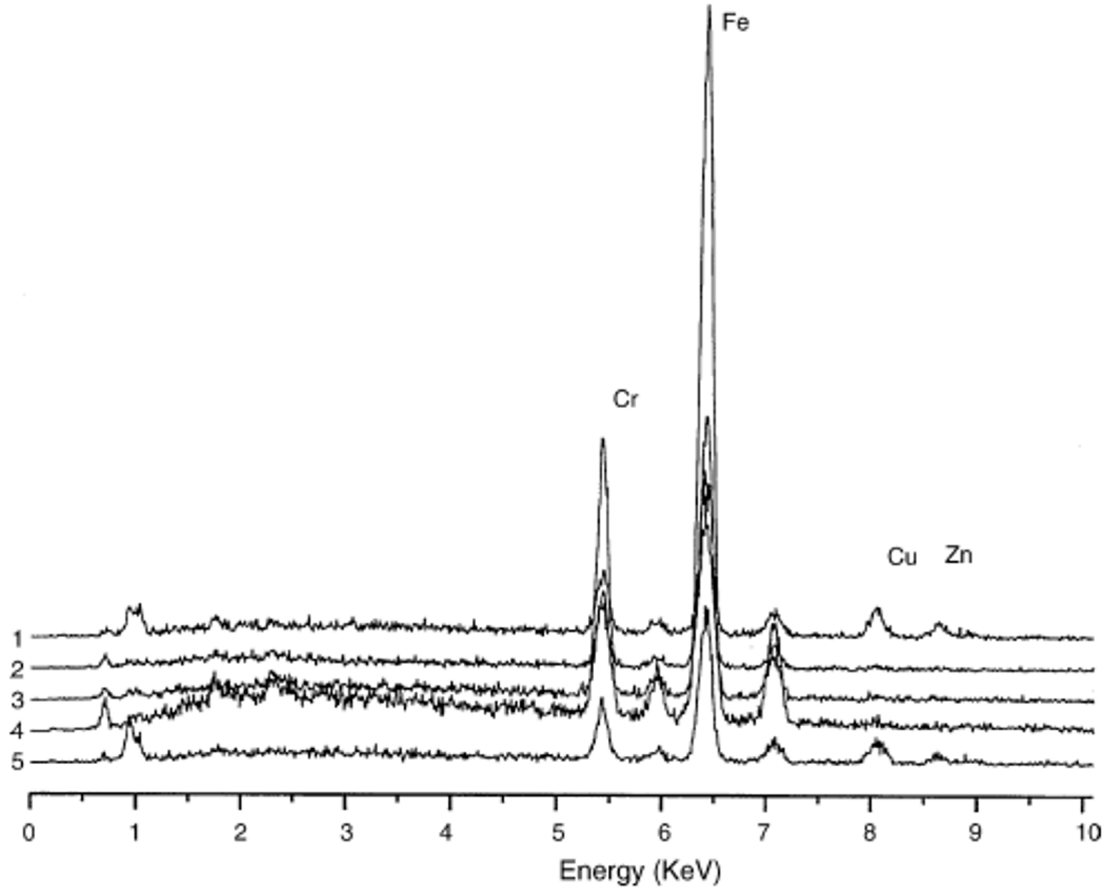

*T. Xi, Materials Science and Engineering: C, (2017)*




*I.T. Hong, Materials Science and Engineering: A, (2005).*

Precipitation of epsilon phase can cause discontinuous passivated film.
Also exhibit galvanic coupling with stainless steel –can be anode or cathode so a hard to predict corrosion response.

# Wire EDM with varying parameters – impact on corrosion




Cu and Zn was abundant in cut 1 and 5, which correlate to the highest passive current density.

All cut surfaces showed an increase in passive current density (correlating to lower corrosion resistance).

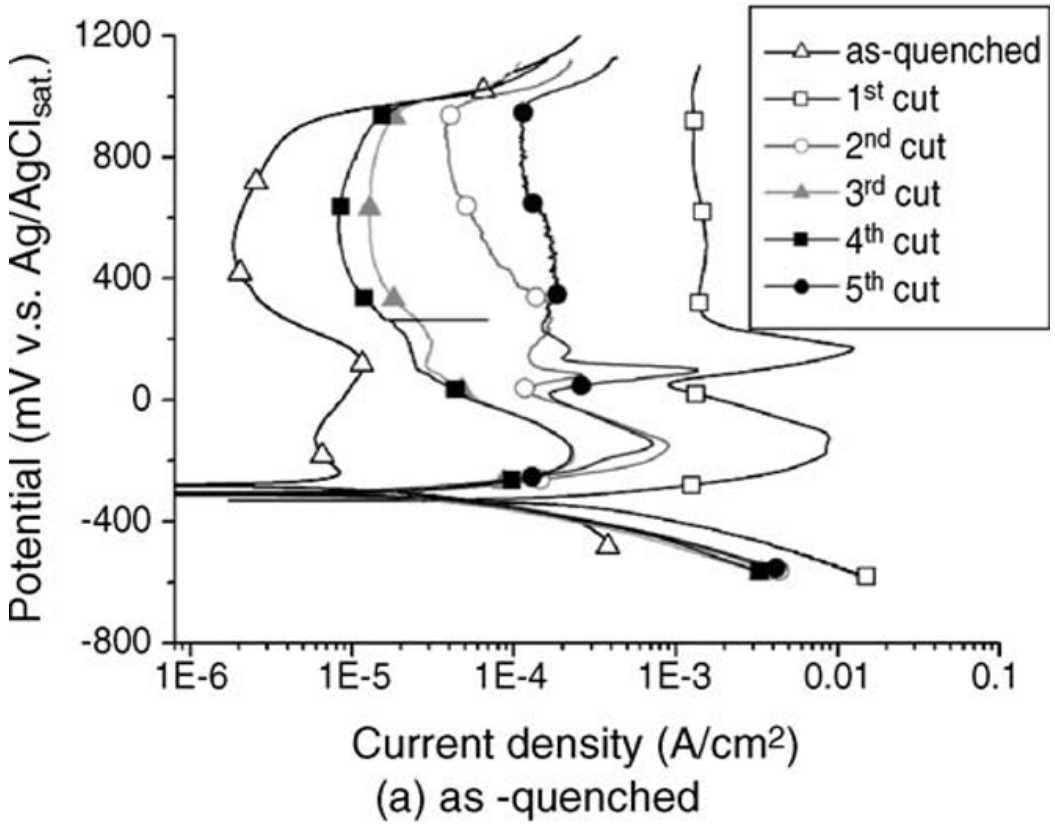
(UUR)

Machining parameters used for multi-cutting passes with WEDM

| Cutting pass | Voltage (V) | CD (A) | TA (μs) | TB (μs) | WS (m/min) | WB (daN) | FP (bar) |
|---|---|---|---|---|---|---|---|
| 1st-cut | −80 | 4 | 1.0 | 9.0 | 10 | 1.0 | 5.5 |
| 2nd-cut | −120 | 8 | 0.2 | 3.8 | 8.0 | 1.4 | 0.8 |
| 3rd-cut | −80 | 16 | 0.4 | 3.0 | 8.0 | 1.4 | 0.8 |
| 4th-cut | −80 | 8 | 0.4 | 3.6 | 8.0 | 1.6 | 0.8 |
| 5th-cut | +120 | 4 | 0.2 | 3.8 | 8.0 | 1.4 | 0.8 |

CD: discharging current; TA: duration of discharging time; TB: time between two pulses; WS: wire feeding speed; WB: wire tension; FP: flushing pressure.

***0.5 M $HClO_4$ and 0.2 M NaCl solution***




***C.A. Huang, Appl. Surf. Sci., (2006)***