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Effects of Surface Finish on the Corrosion Properties of AM 316L SS

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Timothy Gorey, Dan Hooks

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Outline

- Metal Additive Manufacturing (MAM)
- Project Overview
  - Objective and Benefit
  - Surface Roughness Measurements
- Surface Finishing Methods
- Introduction to Aqueous Corrosion Experiments
- As-Built DOE Corrosion Study
  - Results and Observations
- Other Corrosion Results

Additive manufacturing (AM) can be utilized to produce complex geometries that would otherwise be unattainable

Broadening applications as technology continues to improve

Advantages:

- Improved efficiency and design flexibility
- Reduced material usage
- Ability to manufacture complex, topology-optimized parts

Challenges:

- Limited materials
- Very rough surface finish
- Post-build surface finishing is critical

Cunningham, 2017

L. Yang et al, 2019

www.digitalengineering247.com/article/3d-printing-help-hand/

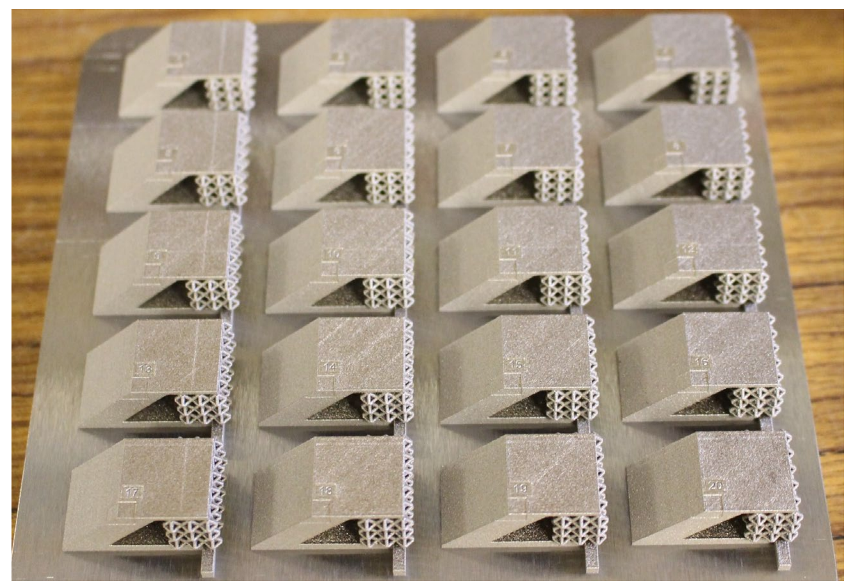

Image courtesy of Michael Melia (SNL)

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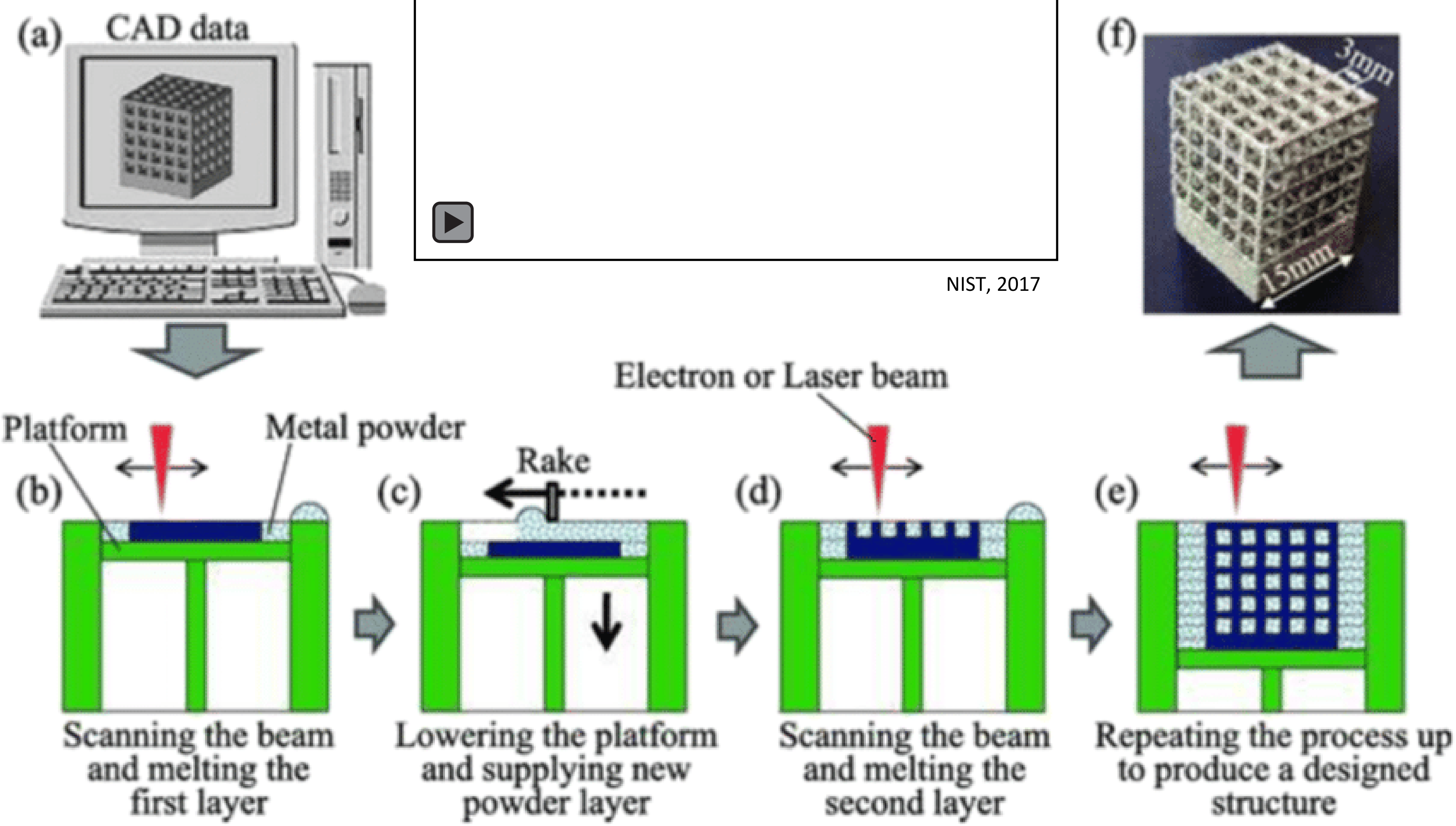
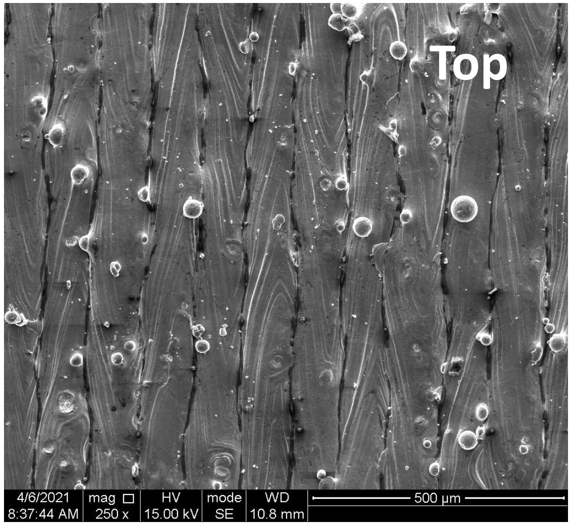
Schematic of the laser powder bed fusion, metal AM process

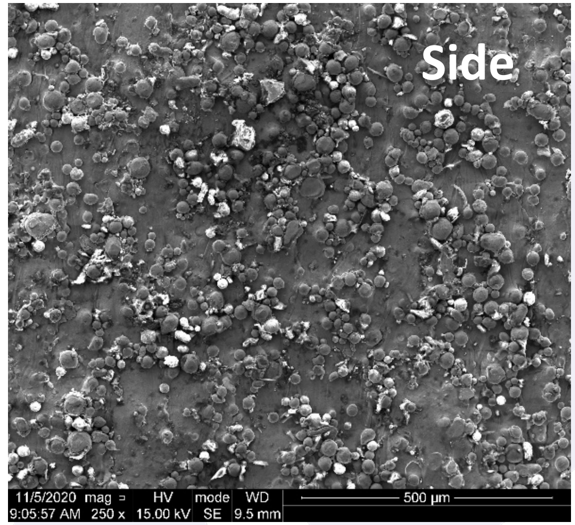
NIST, 2017

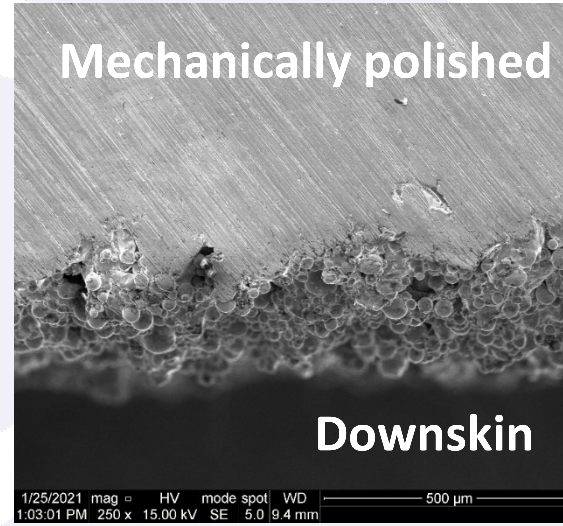


Sibisi et al, 2020, doi: 10.1007/s00170-019-04851-3

As-built surfaces of metal AM parts are extremely different from traditionally manufactured surfaces



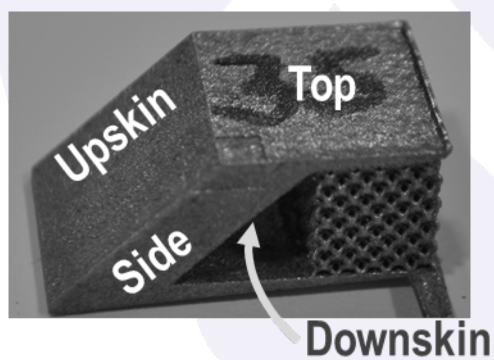




The surface roughness of AM is extremely different from more traditional manufacturing methods and **varies by build angle, machine type, and even location on the build plate**

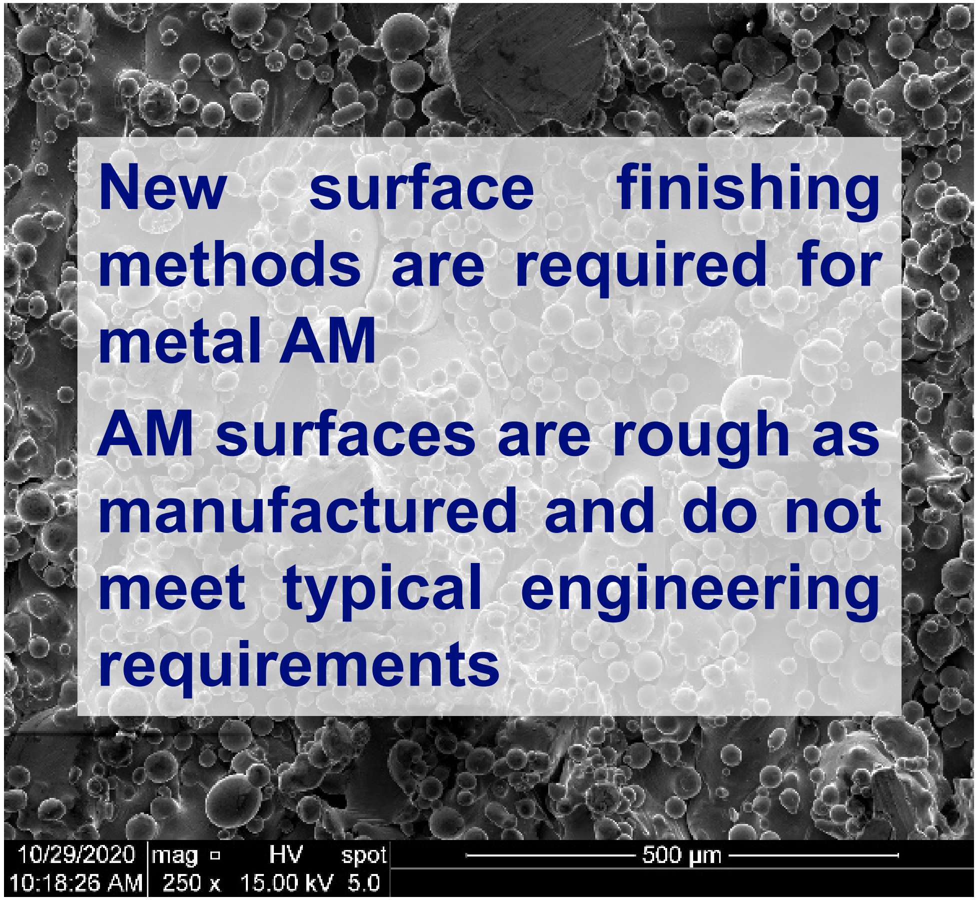
Surface roughness effects:

Corrosion performance
Wear properties
Qualification for production



How do we adapt metal AM to be a drop in replacement for traditional manufacturing?

Metal AM surfaces need to be modified to meet requirements



New surface finishing methods are required for metal AM

AM surfaces are rough as manufactured and do not meet typical engineering requirements

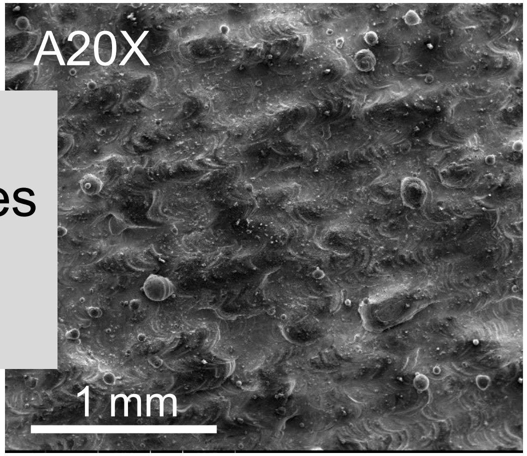
Can we use non-contact methods to achieve surface requirements and retain the desired material properties?

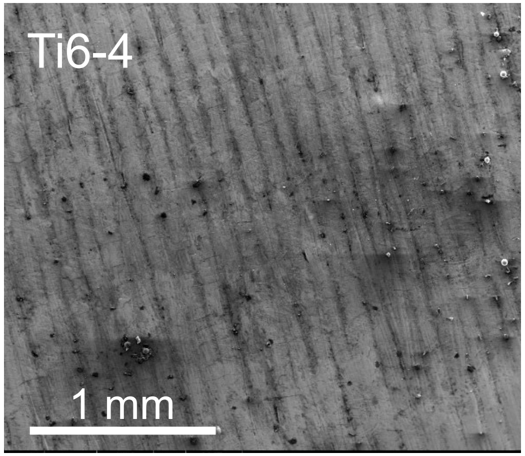
- ✓ Understand the effects of printing and post treatment processes on AM metal surface characteristics and performance
- ✓ Develop solutions to improve surface properties
- ✓ Evaluate corrosion response with respect to functional requirements

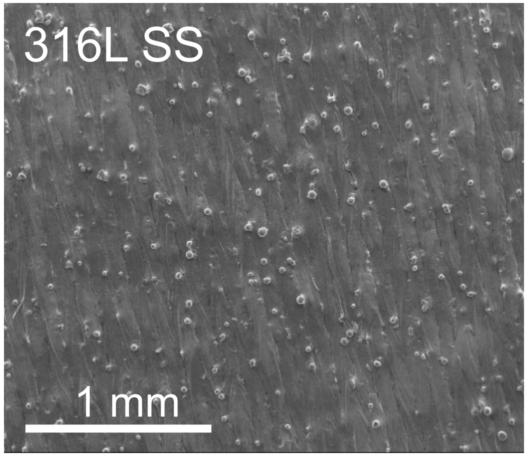
Create an impact across the industry
Address barriers to qualification and product acceptance

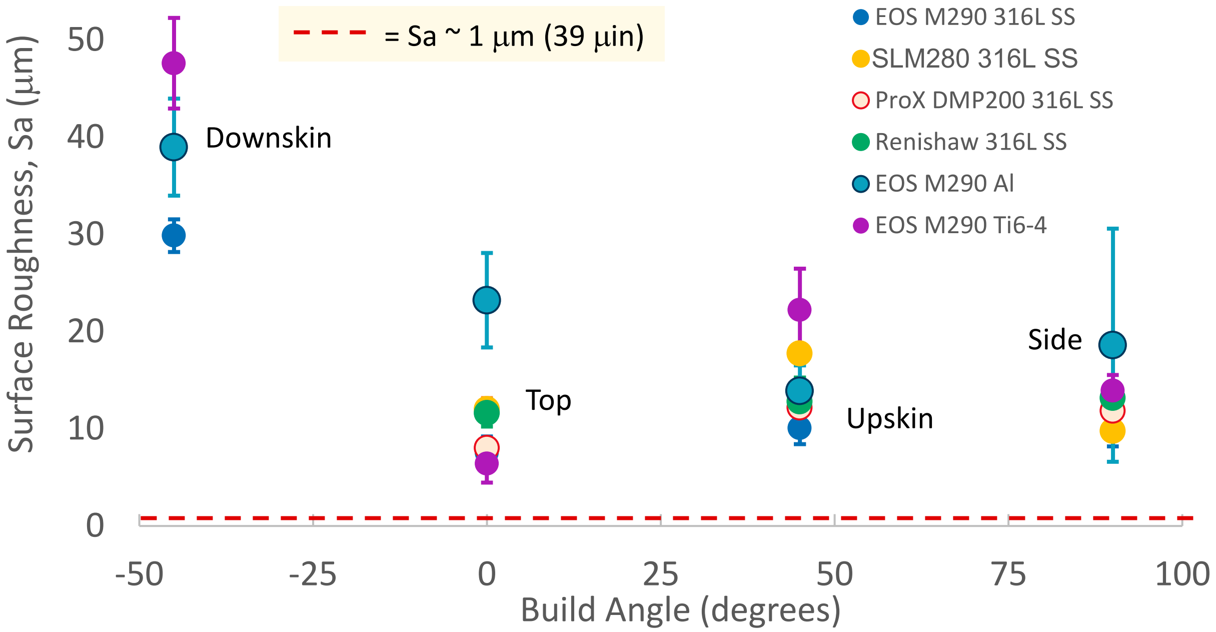
Surface roughness varies by material type, build angle, and machine

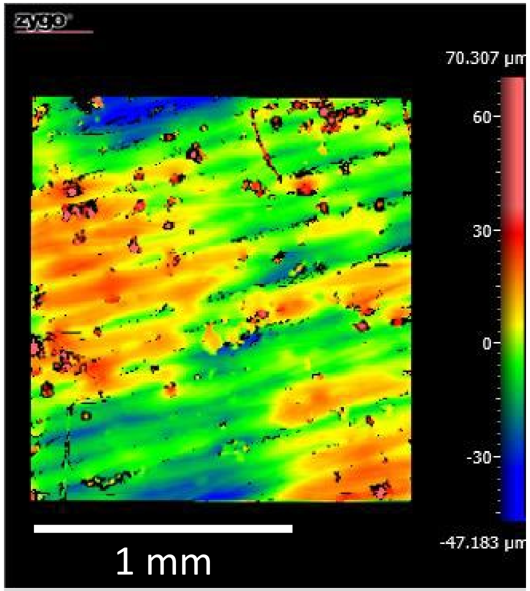
SEM images of AM metal







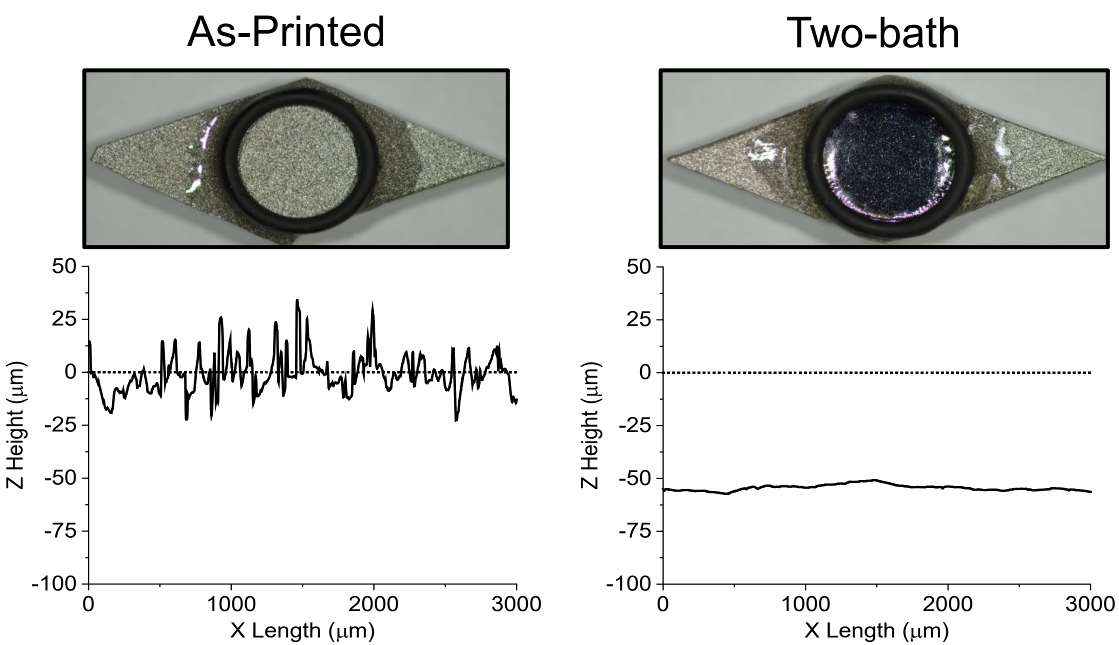




Optical profilometry 316L SS

Multiple methods were used to polish as-built AM material

Pulse/Pulse Reverse Electrochemical Polishing



Electrochemical surface finishing of AM parts (Timothy Gorey – Nov 2, 2:30 – 3:00 pm)

Post processing techniques significantly improve the quality of AM 316L SS

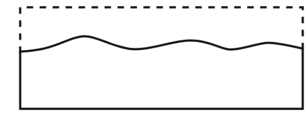
- ✓ Electropolishing: DC, P/PR, two-step
- ✓ DLyte polishing: Solid electrolyte electropolishing
- ✓ Chemical polishing
- ✓ Coatings: Atomic layer deposition (ALD)
- ✓ Thermal annealing and laser peening

Polishing Treatment	Final S_a (µm)	Final S_a (µin)
DC-only	2 – 4	78 – 157
P/PR-only	2 – 4	78 – 118
P/PR + DC	~ 1.0	~ 39
DLyte	~ 1.0	~ 39

Localized corrosion is very common for our systems

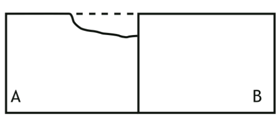
Two main morphologies:

1. Generalized corrosion (uniform corrosion)
   - ➢ Affects the whole surface area exposed to the corrosive environment



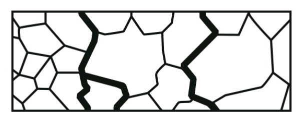
2. Localized corrosion
   - ➢ Takes place on specific sections of the exposed area, due to non-homogeneous surface conditions or the presence of aggressive species

Galvanic corrosion



Occurs when different materials are in contact (material coupling)

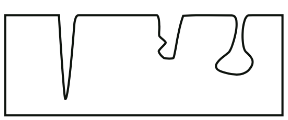
Intergranular corrosion



Preferential degradation at grain boundaries

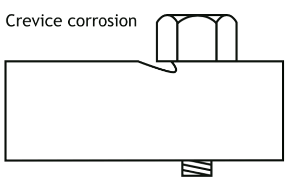
Environmental assisted cracking

Pitting corrosion



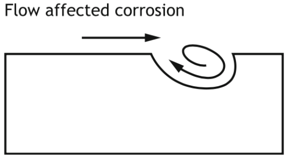
Occurs at inconsistencies in the material's surface, such as breaks in coatings or passive films

Crevice corrosion



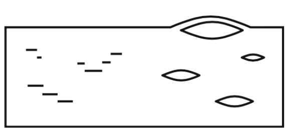
Occurs when a gap is present on the material

Flow affected corrosion



Ex. Erosion-corrosion, impingement corrosion

Hydrogen damage



Ex. Hydrogen embrittlement – crack, blistering, and bulge formation

Images and descriptions from P. Pedeferri, in Corrosion Science and Engineering, p. 5–7, Springer (2019).

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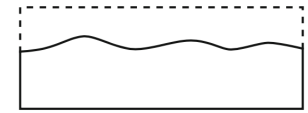
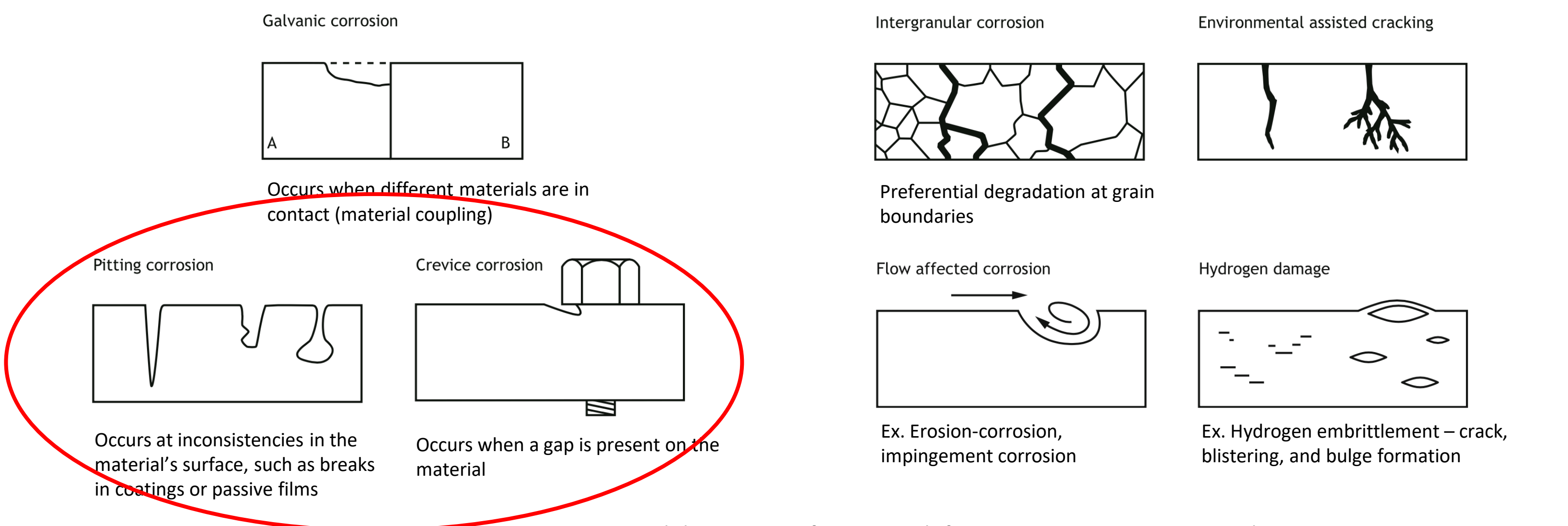


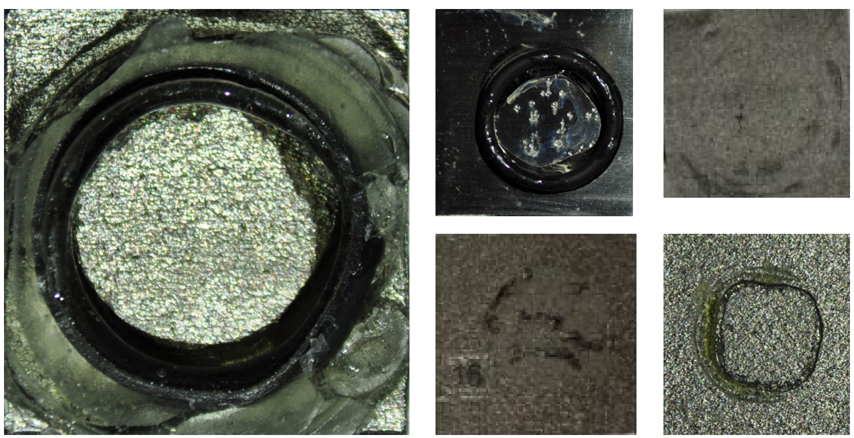


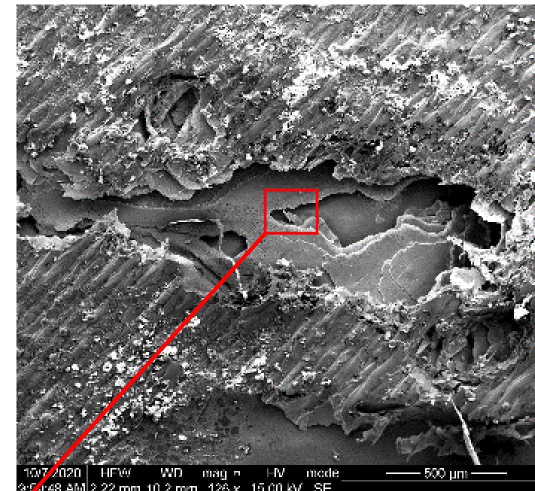
Images and descriptions from P. Pedeferri, in Corrosion Science and Engineering, p. 5–7, Springer (2019).

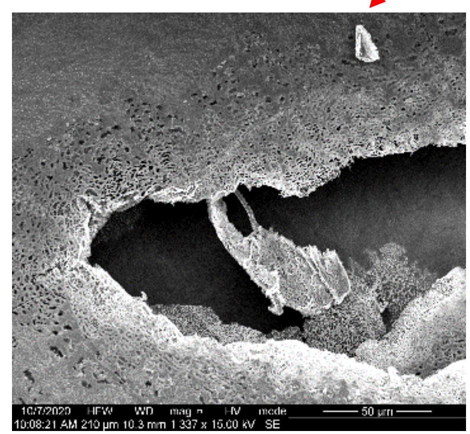
Pitting and crevice corrosion are regularly observed in aqueous corrosion measurements

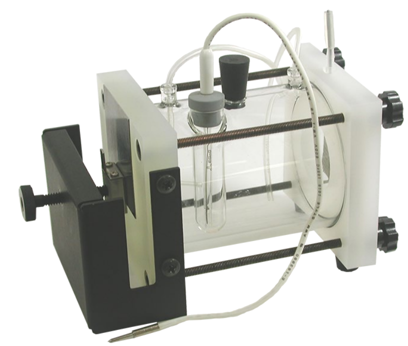
Localized corrosion, in the form of **pitting** and **crevice** corrosion, has been prominent

Sealing the O-ring/surface interface with epoxy helps to minimize crevice corrosion









K0235 Flat Cell Kit for Corrosion Testing – Princeton Applied Research (AmetekSI)

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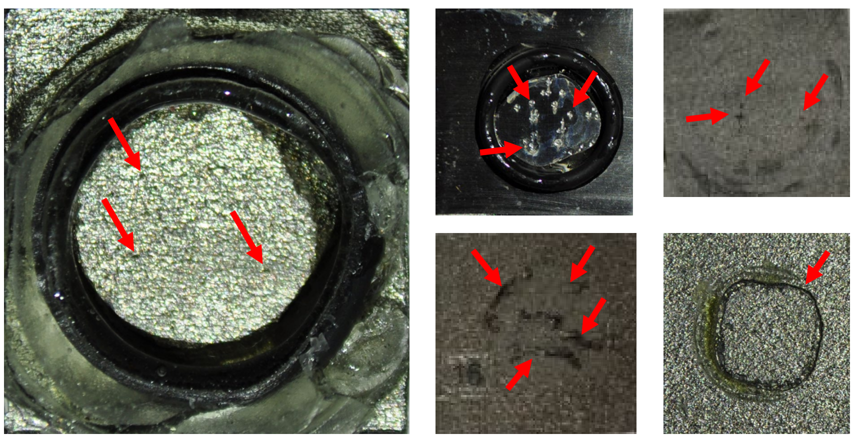
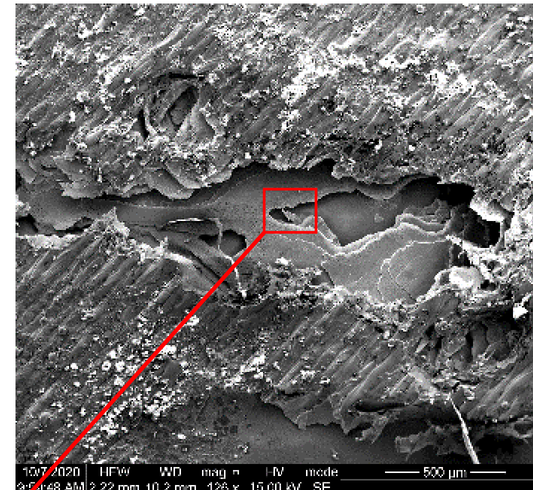
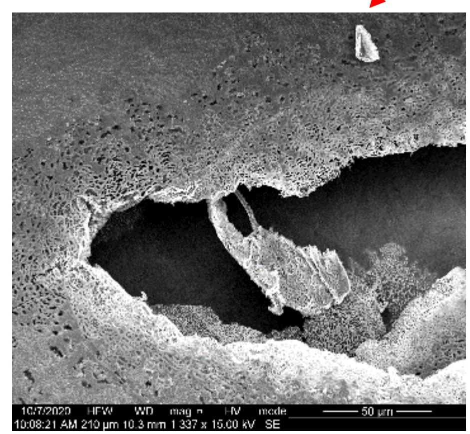
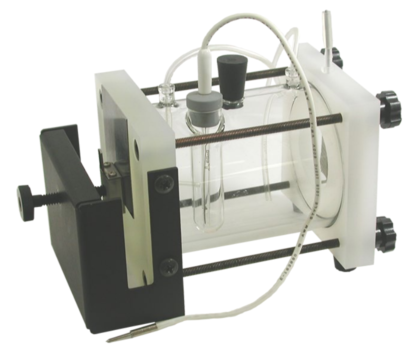




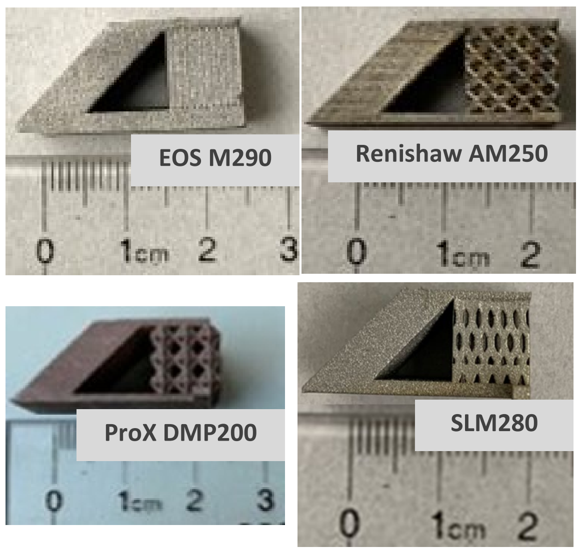




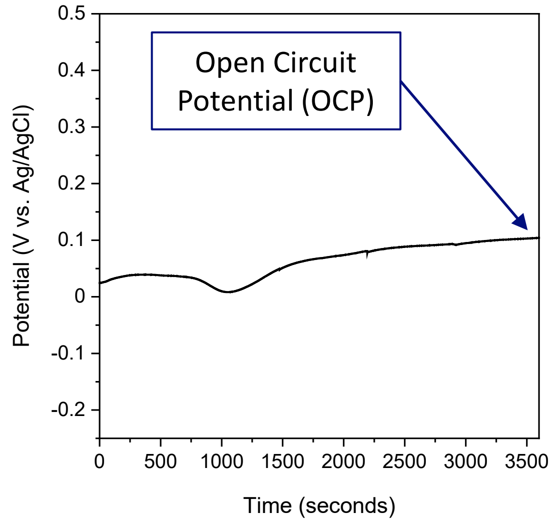
K0235 Flat Cell Kit for Corrosion Testing – Princeton Applied Research (AmetekSI)

Accelerated aqueous corrosion measurements that are frequently used

Parts from different machines

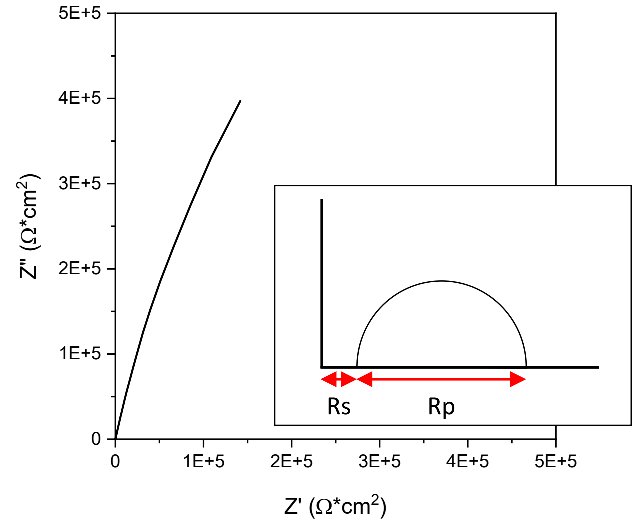


Open Circuit Potential



Shows interaction between sample and electrolyte

Electrochemical Impedance Spectroscopy

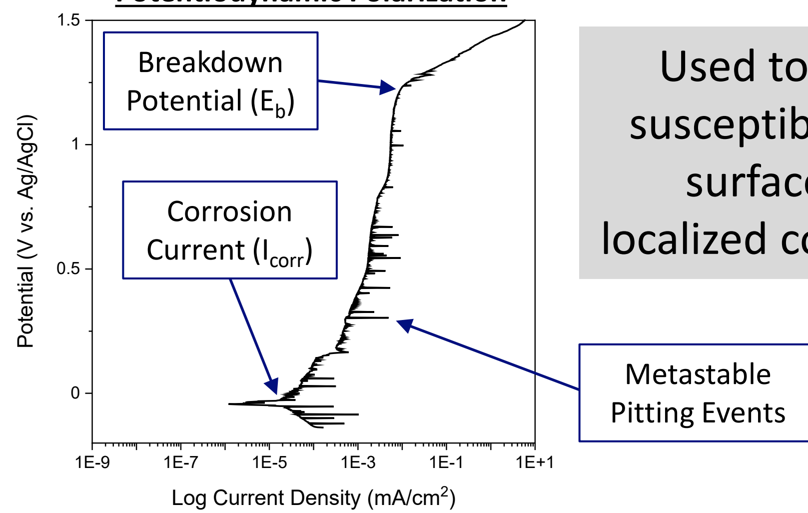


Can provide indication of surface oxide stability

Aqueous corrosion measurements allow for rapid analysis of corrosion performance

Electrolyte representative of the production system should be used for these experiments

Potentiodynamic Polarization



Used to rank susceptibility of surface to localized corrosion

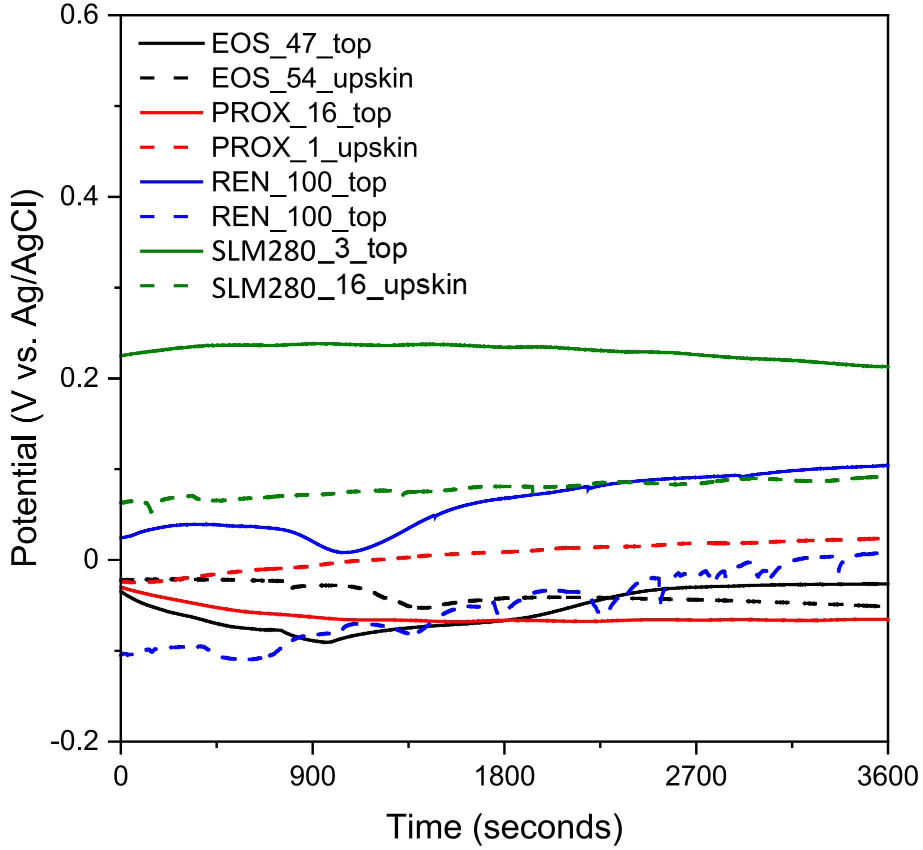
Open circuit potential measurements are used to ensure system is in equilibrium

Corrosion Environment: 3.5 wt% NaCl

Measurement Time: 1 hour

Passive electrochemical technique

Stable value is taken as the OCP reference for subsequent electrochemical experiments



Signal stabilizes for all sample surfaces

Potentiodynamic polarization measurements are used to rank localized corrosion susceptibility

Potential range: -0.02 V vs. E_{OC} to 1.5 V vs. Ref

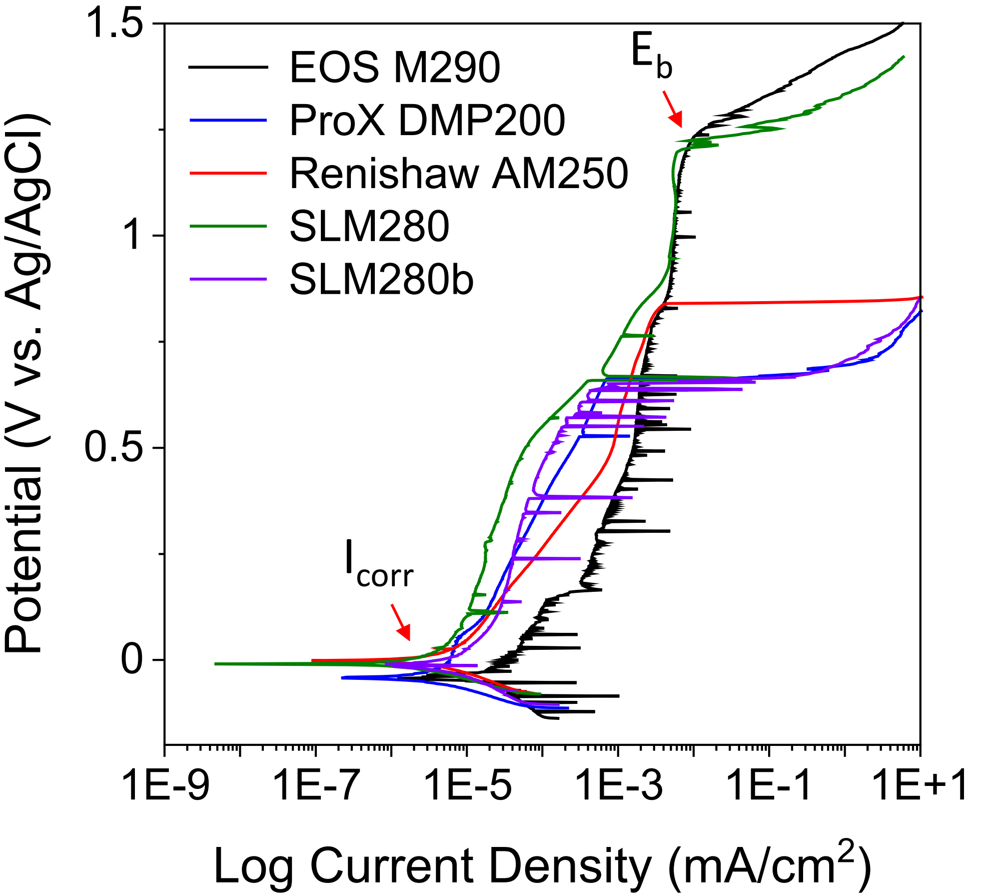
Scan rate: 0.167 mV/s

Breakdown potential (E_b) consistently **~1.2 V vs Ag/AgCl** for EOS samples

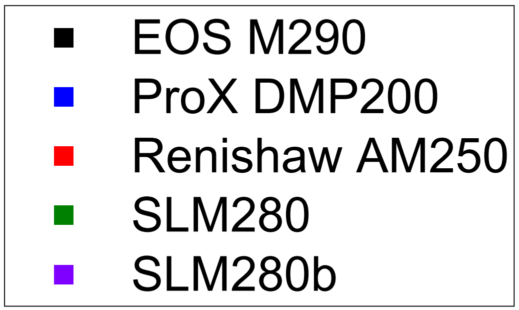
- SLM280 instrument also maintained consistently high E_b values

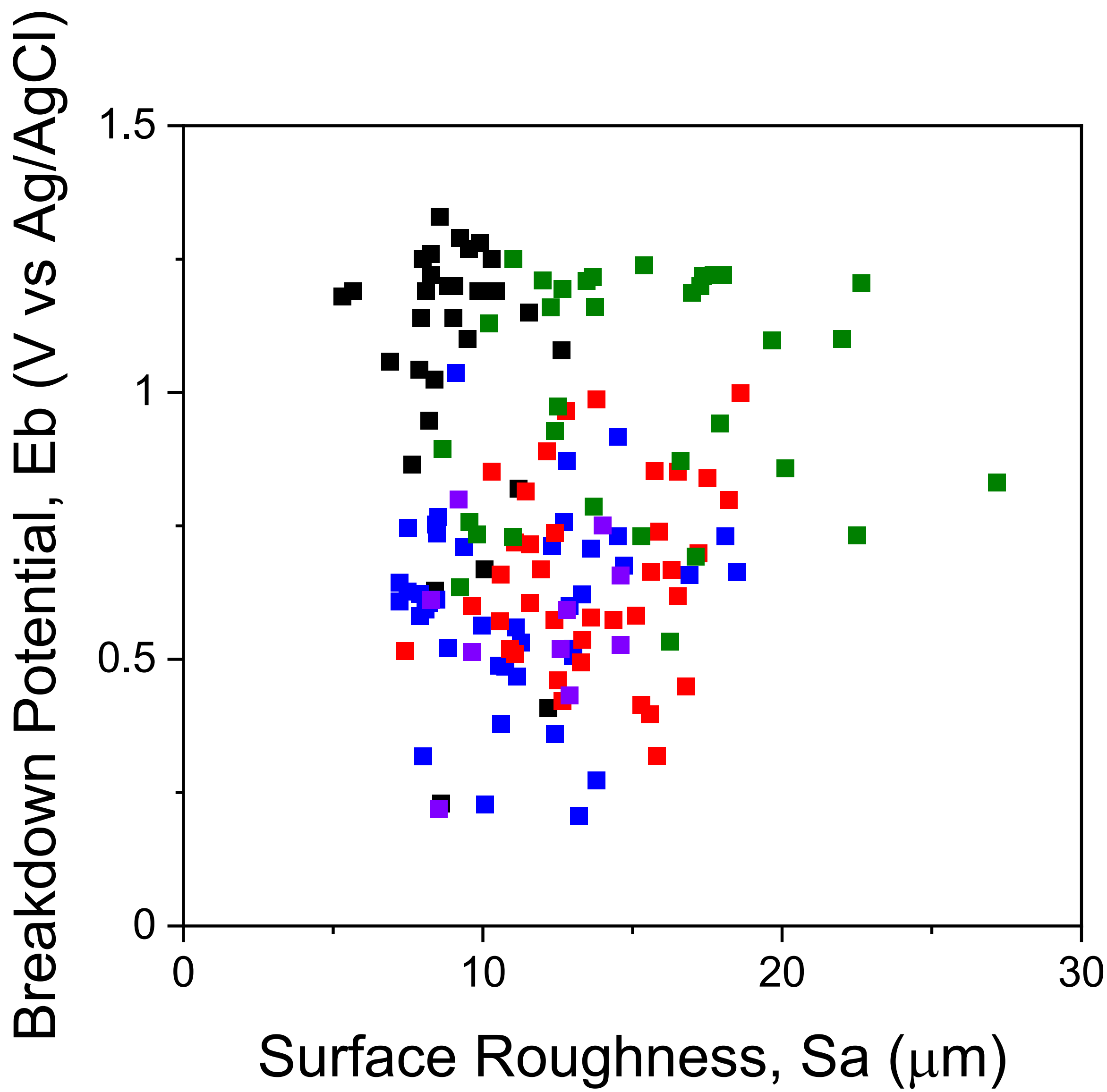
Metastable pitting events occur frequently for as-built surfaces

Corrosion current (I_{corr}) similar across metal AM machines

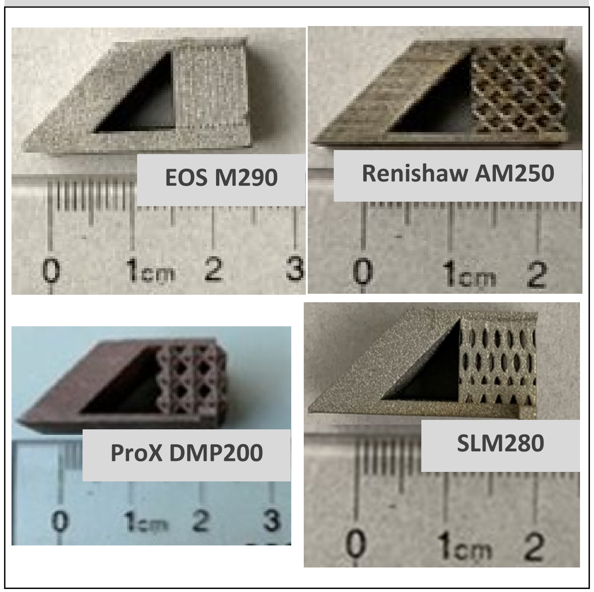


A large number of samples were tested at all sites





Parts from different machines



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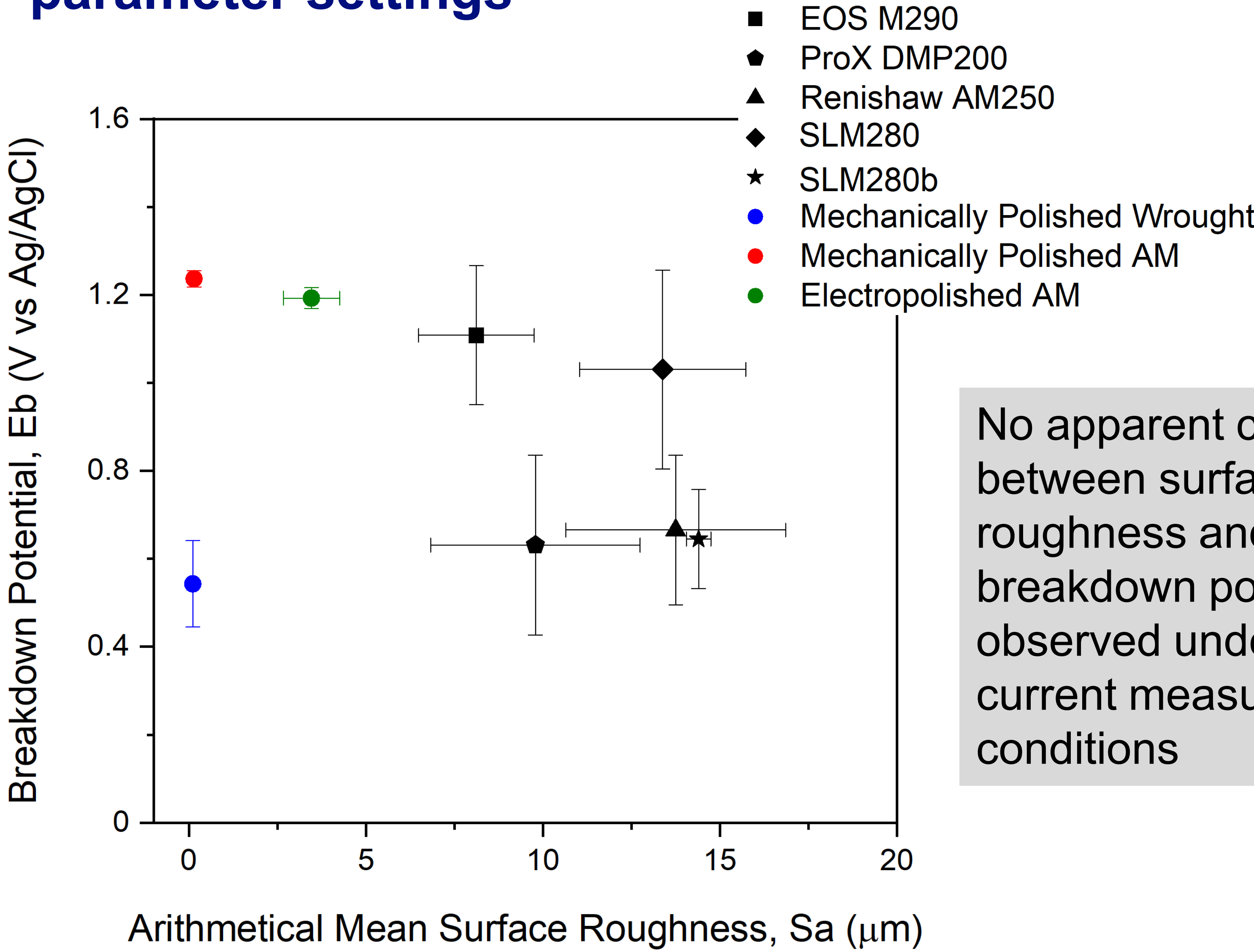
Breakdown potential depends on build machine and parameter settings



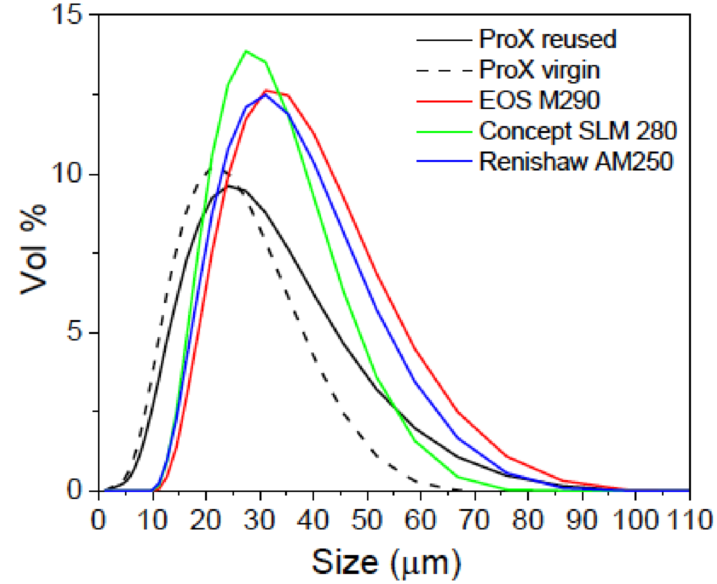
No apparent correlation between surface roughness and breakdown potential was observed under the current measurement conditions

Powder analysis confirmed that all starting material falls within range of the manufacturer's specification

SEM images of powder

Composition determined by ICP-MS and LECO

Powder analysis with laser diffraction



	ProX DMP200 virgin	EOS M290 reused	Concept reused	Renishaw reused
Apparent Density (g/cc)	3.64	4.45	4.54	4.48
ASTM B964 Carney Flow (sec./100 g.)	-	5.6	7.9	8.1
Carr Index	25.71	14.42	14.02	14.34
Hall Flow ASTM B213 (sec./50 g.)	-	13.7	12.5	12.8
Hausner Ratio	1.3	1.2	1.2	1.2
Skeletal Density (g/cc)	7.7681	7.8266	7.8364	7.8297
Tap Density (g/cc)	4.9	5.2	5.28	5.23

Wt%	Al	C	Cr	Cu	Fe	H	Mn	Mo	N	Ni	O	P	S	Si	V
ProX virgin	0.004	0.018	16.95	0.16	68.2	0.0004	1.08	2.09	0.12	10.5	0.071	0.018	0.009	0.65	0.035
ProX reused	0.012	0.021	16.9	0.17	68.1	0.0004	1.09	2.1	0.11	10.55	0.093	0.018	0.011	0.66	0.036
EOS M290	0.001	0.024	17.9	0.013	65.2	0.0001	0.77	2.21	0.11	12.94	0.036	0.005	0.005	0.73	0.023
SLM280	0.001	0.024	17.91	0.033	65.2	0.0002	0.78	2.17	0.11	12.95	0.046	0.006	0.007	0.69	0.027
Renishaw	0.007	0.016	17.15	0.006	66.5	0.0002	1.27	2.35	0.01	11.98	0.051	0.005	0.005	0.56	0.003

Courtesy of NSL Analytical

EBSD analysis revealed large variation in mean grain size between samples built on different machines

A - EOS M290

Grain Count: 2366

Mean: 852.6μm²

B - ProX DMP200

Grain Count: 2219

Mean: 360.9μm²

C - SLM280

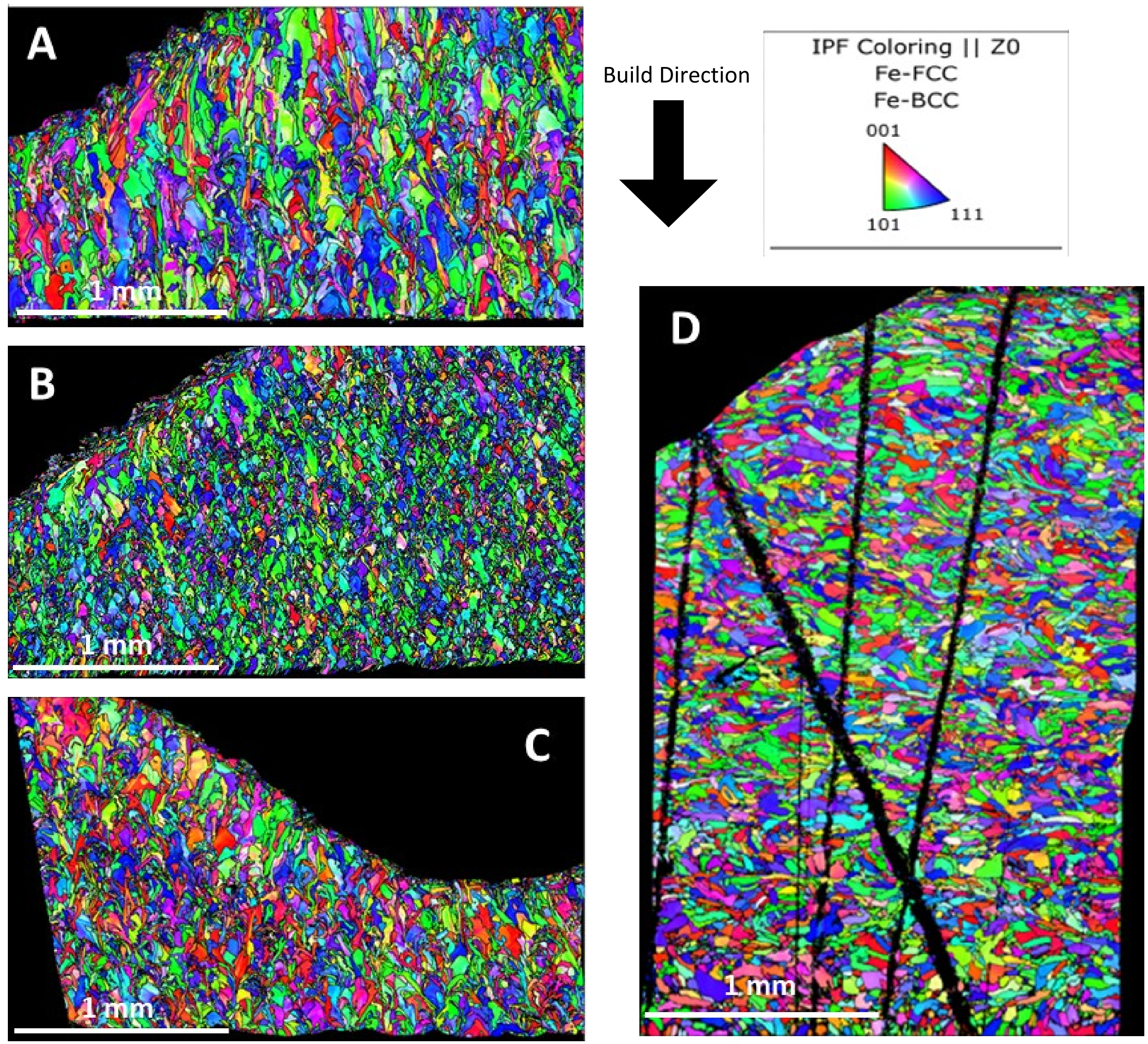
Grain Count: 2174

Mean: 521.4μm²

D - Renishaw AM250

Grain Count: 2088

Mean: 291.8μm²



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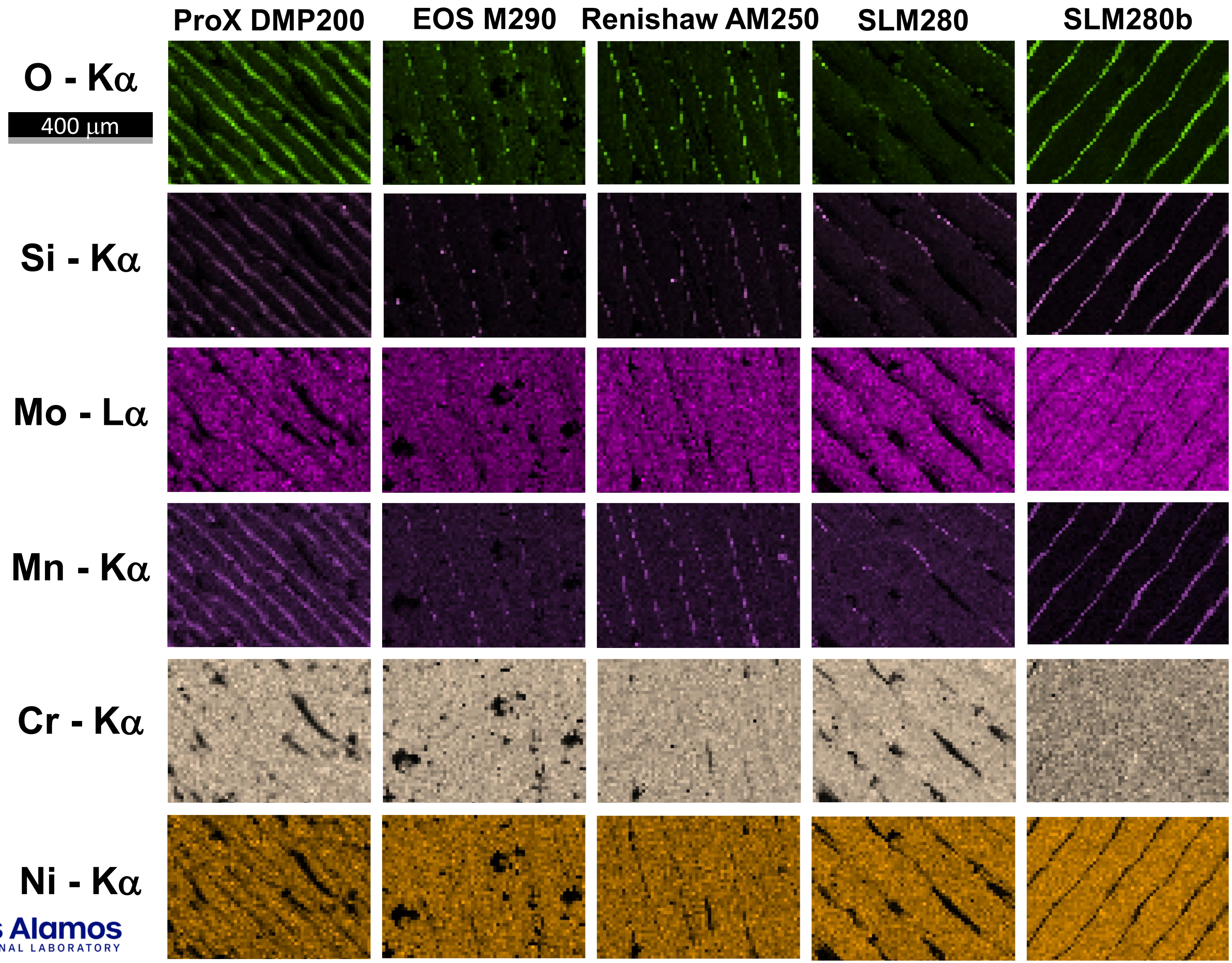
SEM/EDS – Chemical segregation may affect corrosion performance



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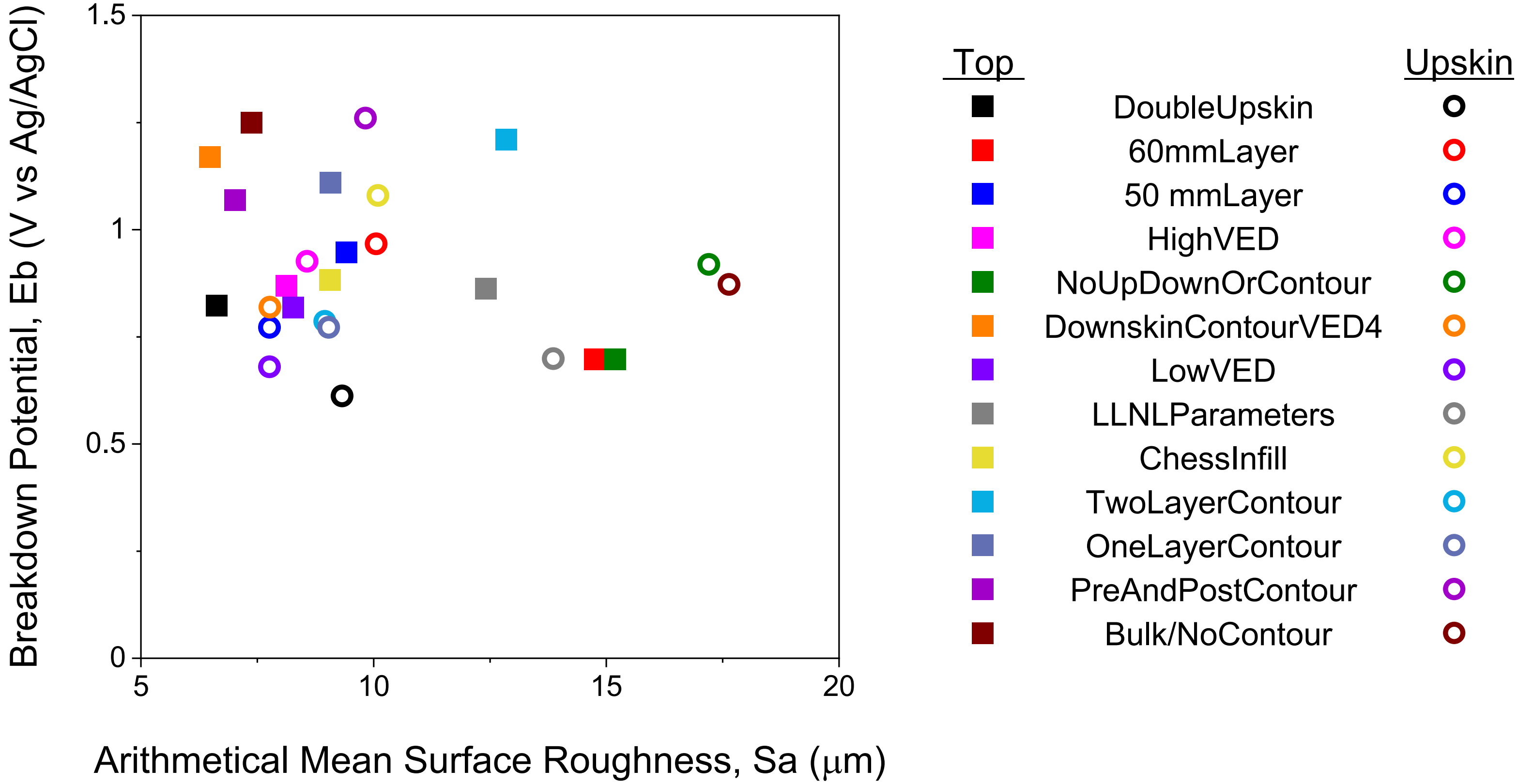
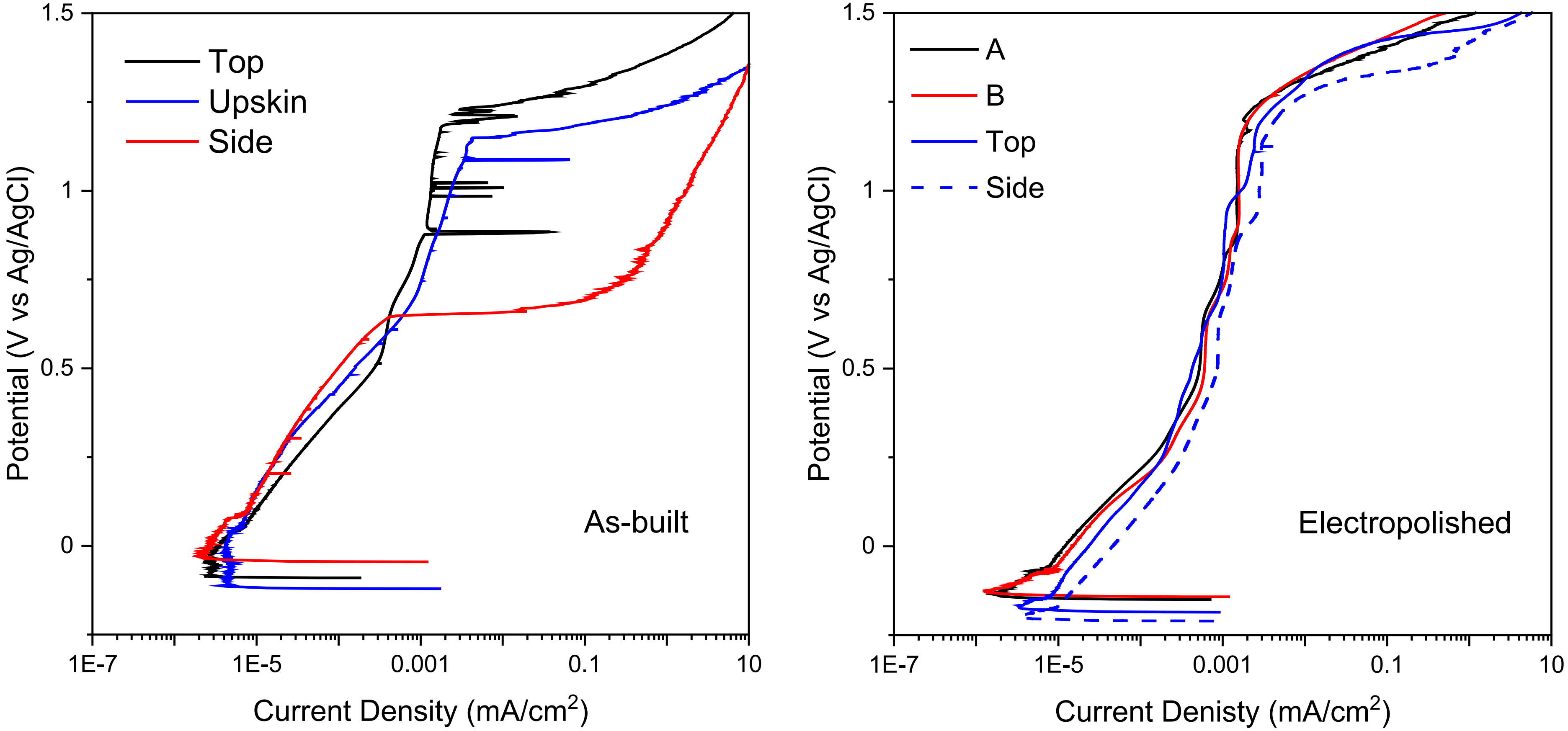
Build parameters greatly effect corrosion behavior of the resulting parts



No direct correlation seen in performance of a single sample when comparing top and side surfaces

Large deviations in measured E_b value

Electropolishing surfaces decreases susceptibility to localized corrosion and improves consistency in corrosion performance



Electropolished samples have increased breakdown potentials and fewer metastable pitting events

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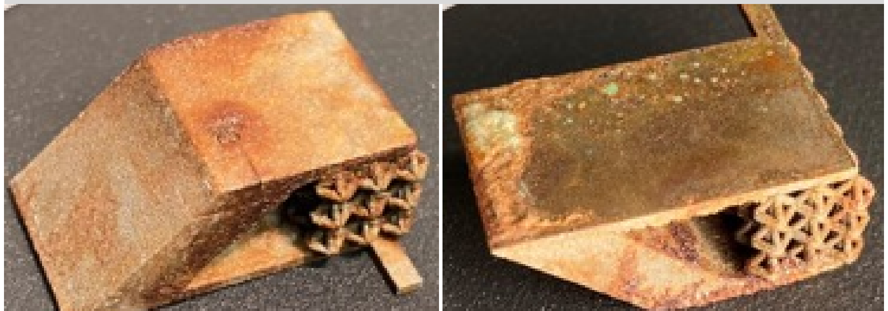
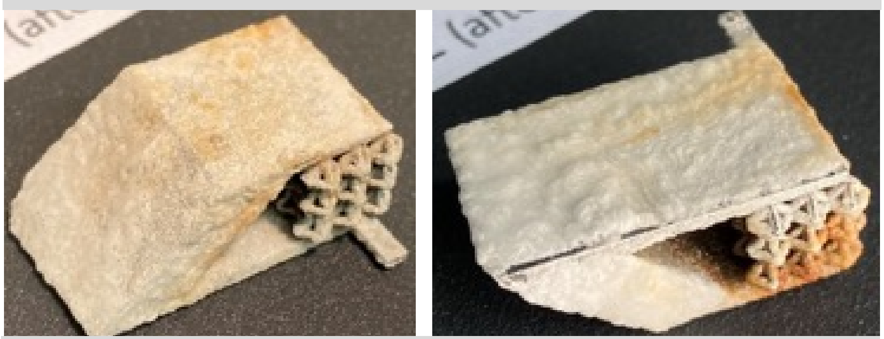
Atmospheric corrosion experiments correlate with aqueous corrosion tests

Top angled view | **Cut surface view**

ProX DMP200 As-printed

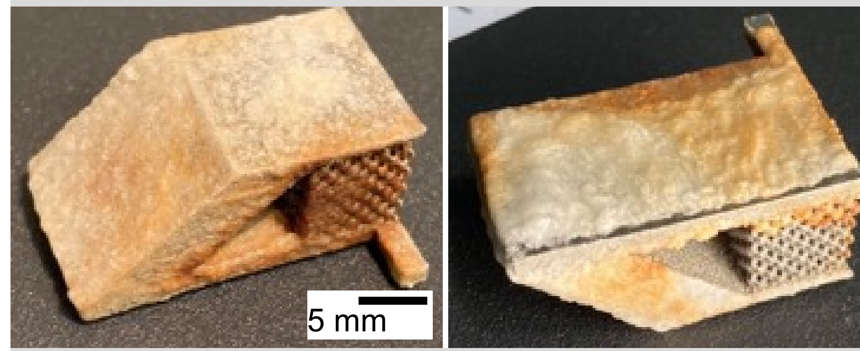


ProX DMP200 Electro-polish



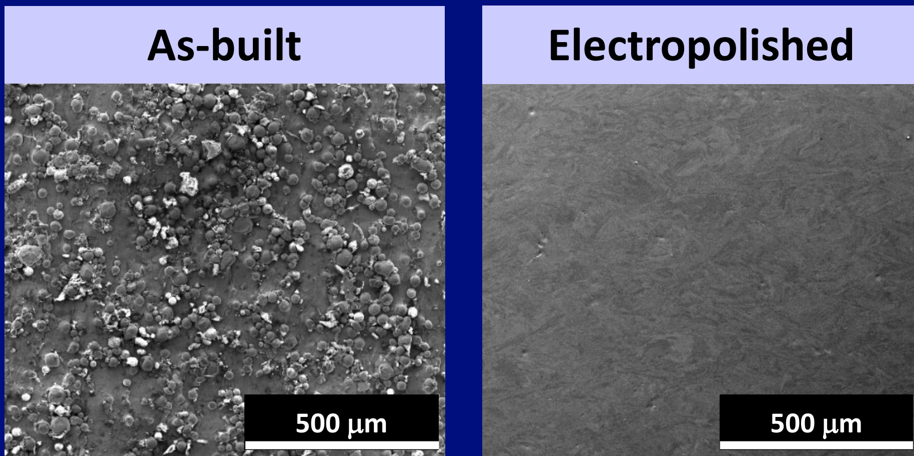
Top angled view | **Cut surface view**

EOS M290 As-printed

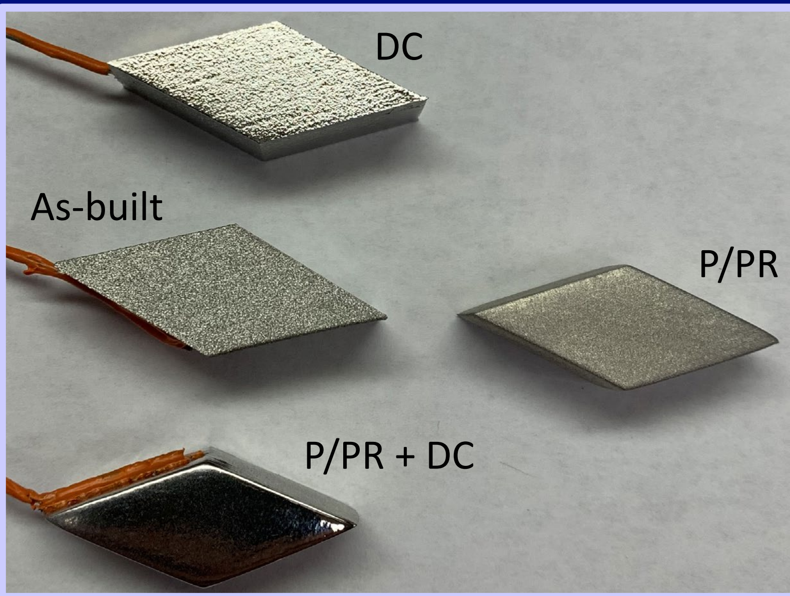


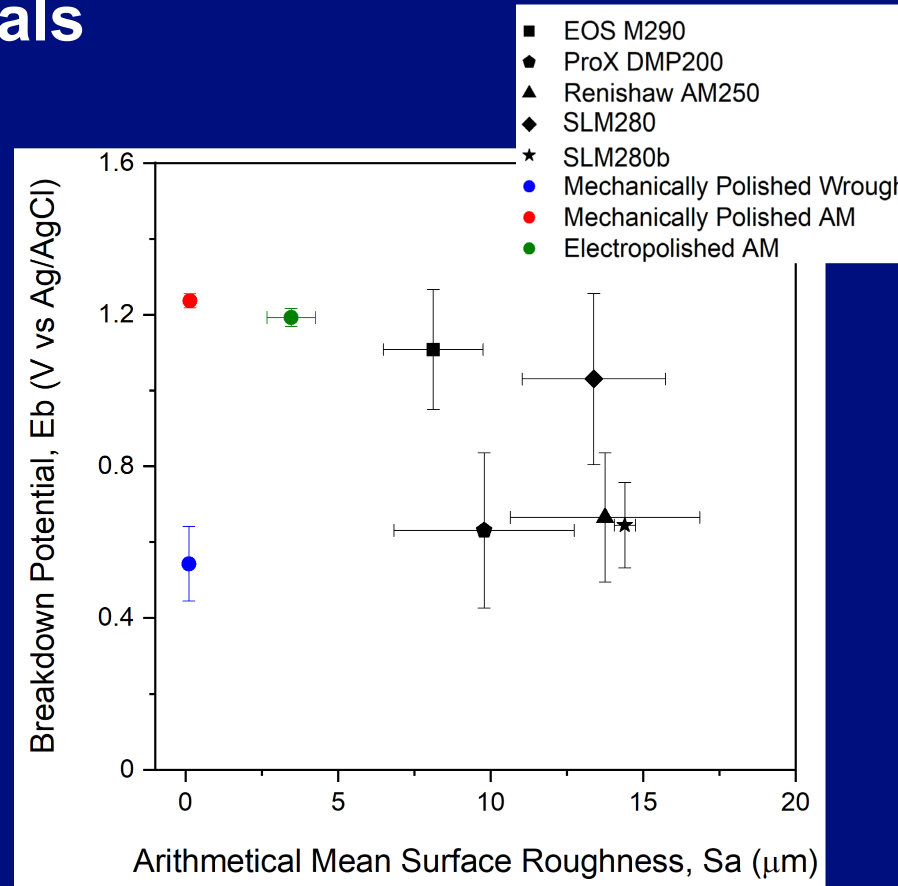
Samples after 600 hour exposure to ASTM G85-A2 at UVA

Summary of how surface finishing can be used to adapt the surface of AM metals



SEM of as-built 316L SS and electropolished side surfaces, final surface roughness 1.0 mm (39 min)





<u>We are adapting metal AM to be a drop in replacement for traditional manufacturing</u>

Key Points

- Metal additive manufacturing allows for complex geometries to be fabricated that are unattainable using conventional manufacturing techniques
  - The as-built surfaces of these parts are extremely rough
- Surface roughness and corrosion performance of as-built coupons varies widely with build angle, machine type, and location on the build plate
  - Corrosion performance does not show a direct correlation to surface roughness
- Electropolishing drastically improves corrosion performance of AM 316L SS!

Thank You to All Collaborators!

LANL: Colt Montgomery, Robin Pacheco, Robert Hackenberg, and Eric Tegtmeier

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

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