Challenges of additively manufactured materials under molten salt corrosion

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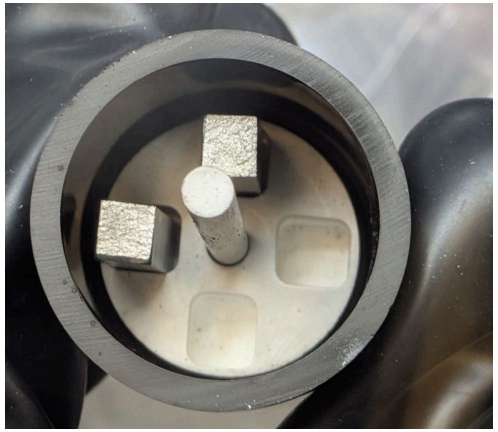
AMMT Molten Salt Corrosion - FY26 Tasks at INL

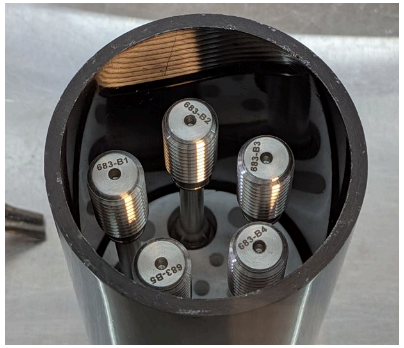
Task 1: Static corrosion of LPBF 316H stainless steel and wrought Alloy 244 in NaCl-$MgCl_2$ salts

Crucible setup - static immersion in molten chloride salt

LPBF 316H specimens in crucible: as-deposited and machine-cut



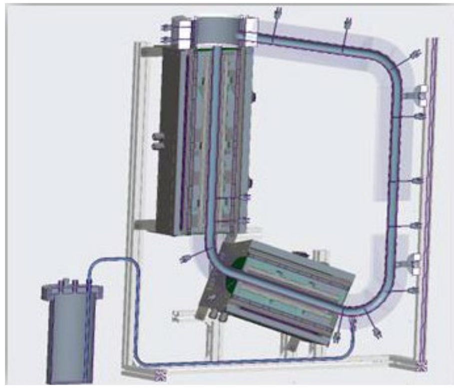
Task 2: Ex situ mechanical testing of LPBF SS316H in NaCl-$MgCl_2$



Wrought SS316 exposure complete

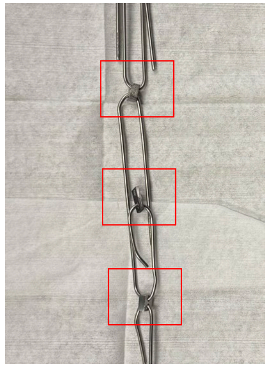
Creep testing of exposed will start soon

Task 3: Corrosion testing of LPBF SS316H and wrought Alloy 244 in flowing LiCl-KCl



Cross section of INL thermal convection loop

Wrought and LPBF samples in loop sample chain



Additive Manufacturing in Extreme Nuclear Environments

ADDITIVE MANUFACTURING

Design freedom for next-generation components

- Complex geometries & internal channels
- Compact heat exchangers for nuclear systems
- Rapid fabrication & reduced lead times

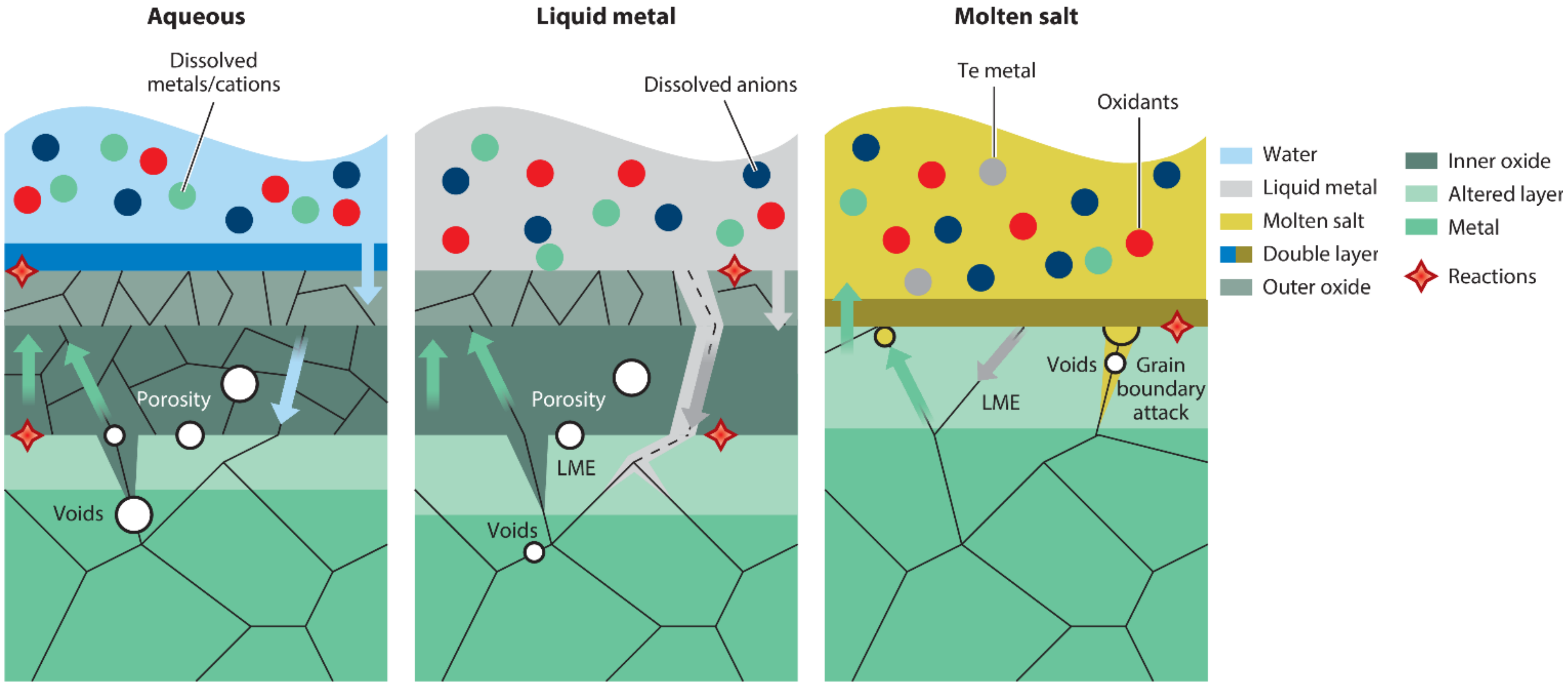
NUCLEAR ENVIRONMENTS

Among the most aggressive conditions for materials

- High temperatures & reactive coolants
- Molten salt - sustained ionic attack on structural alloys
- Material compatibility governs component lifetime

AM components enter molten salt service, corrosion emerges as the key materials challenge

Molten salt corrosion – a primary degradation mode



Schmidt F, et al. 2021. Annu. Rev. Mater. Res. 51:293 328

Unlike aqueous systems, molten salt corrosion demands dedicated attention in material qualification

Factors governing molten salt corrosion - a materials view

Salt Environment

Salt Chemistry
Composition, Impurities

Salt Purity
Oxide content, Moisture

Temperature
Kinetics, Exposure time

Material Properties

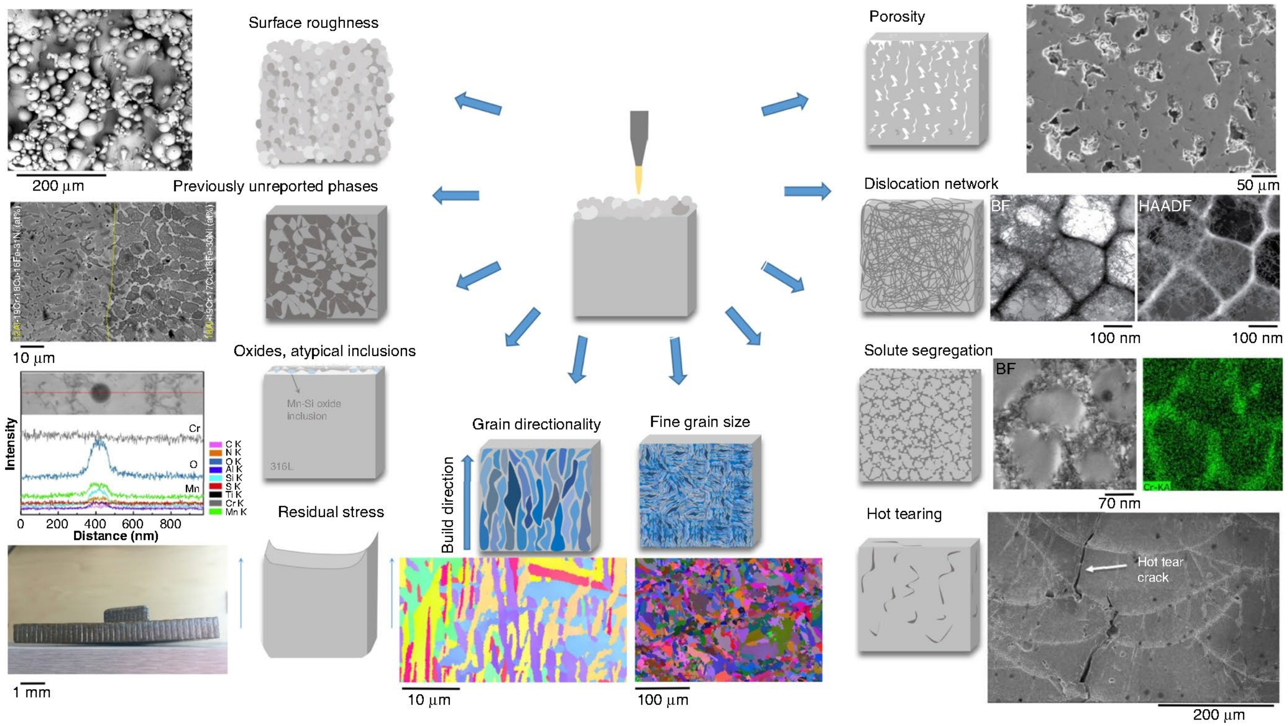
Microstructure
Grain boundary, porosity

Wetting
Salt-metal interface contact

Surface condition
Roughness, oxides, slag

Surface condition and microstructure are the material variables that determine corrosion response - and both are uniquely complex in additively manufactured materials

AM produces inherent complexity - both microstructure and surface



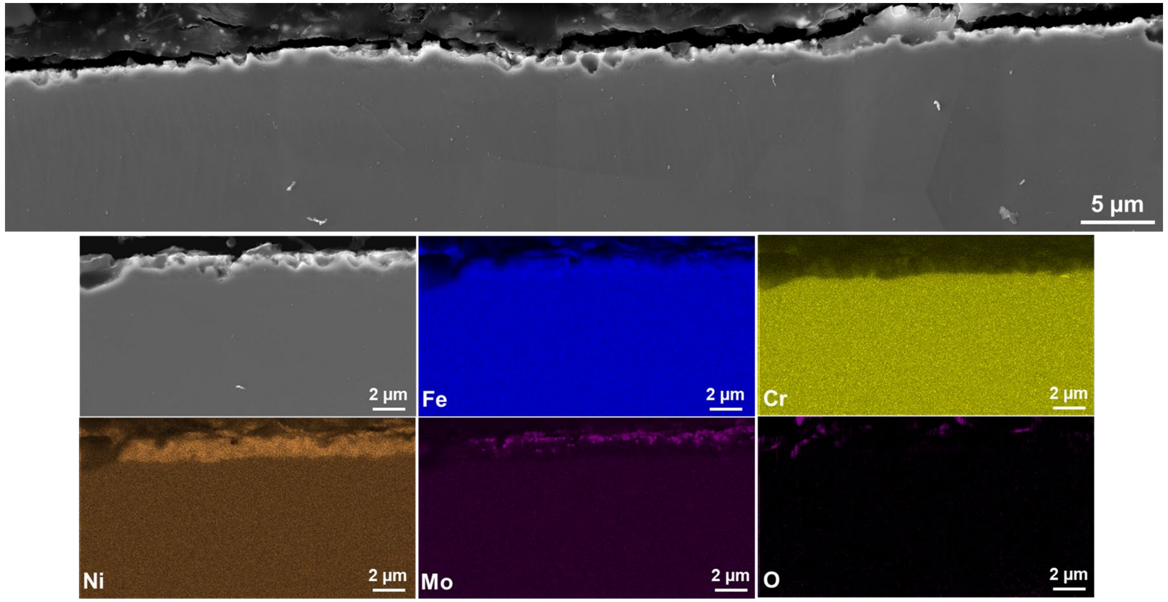
G. Sander, et al. 2018. Corrosion. 74:1318 - 1350

MICROSTRUCTURE
Heterogeneous and anisotropic
Columnar grains, porosity, residual stress, solute segregation - vary with build direction and process parameters

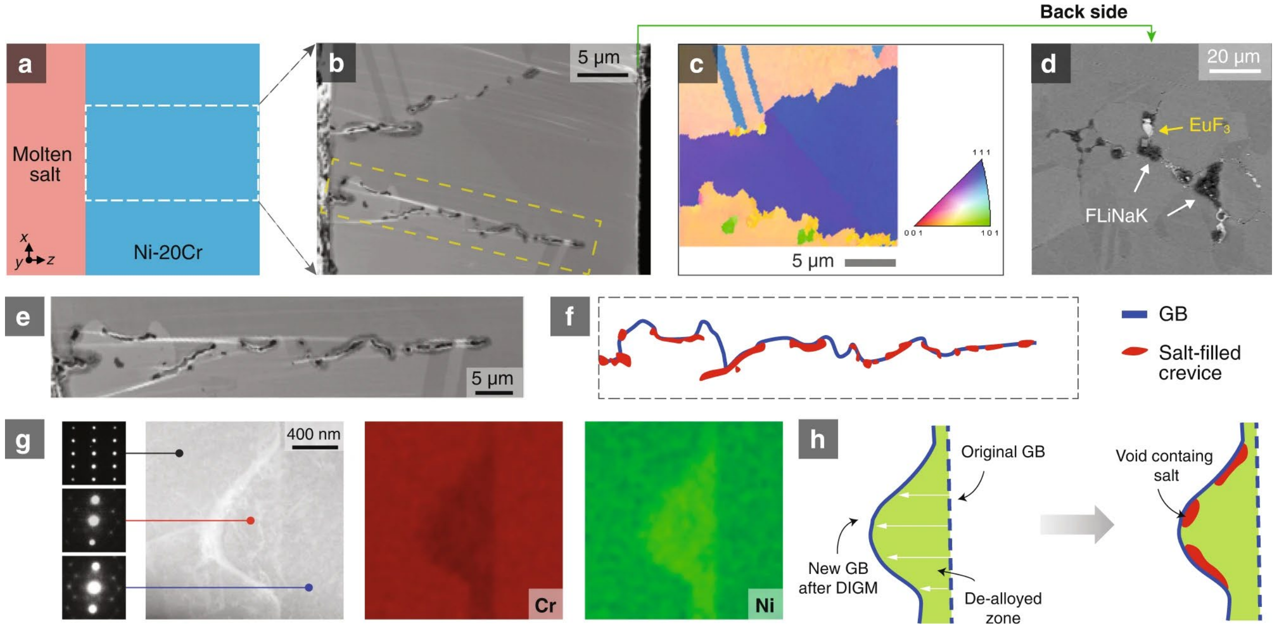
SURFACE CONDITION
Complex and process-dependent
As-deposited surfaces carry roughness, oxides, and process artifacts - the real interface between material and environment

AM introduces microstructural and surface features that warrant dedicated consideration in corrosion assessment

Molten salt corrosion - current research focus



Polished AM 316H stainless steel surface



Ni-20Cr Binary alloy polished sheet

Y. Yang, et al. 2023. Nat Commun. 14:988

Systematic Cr depletion and Ni enrichment in the corroded layer

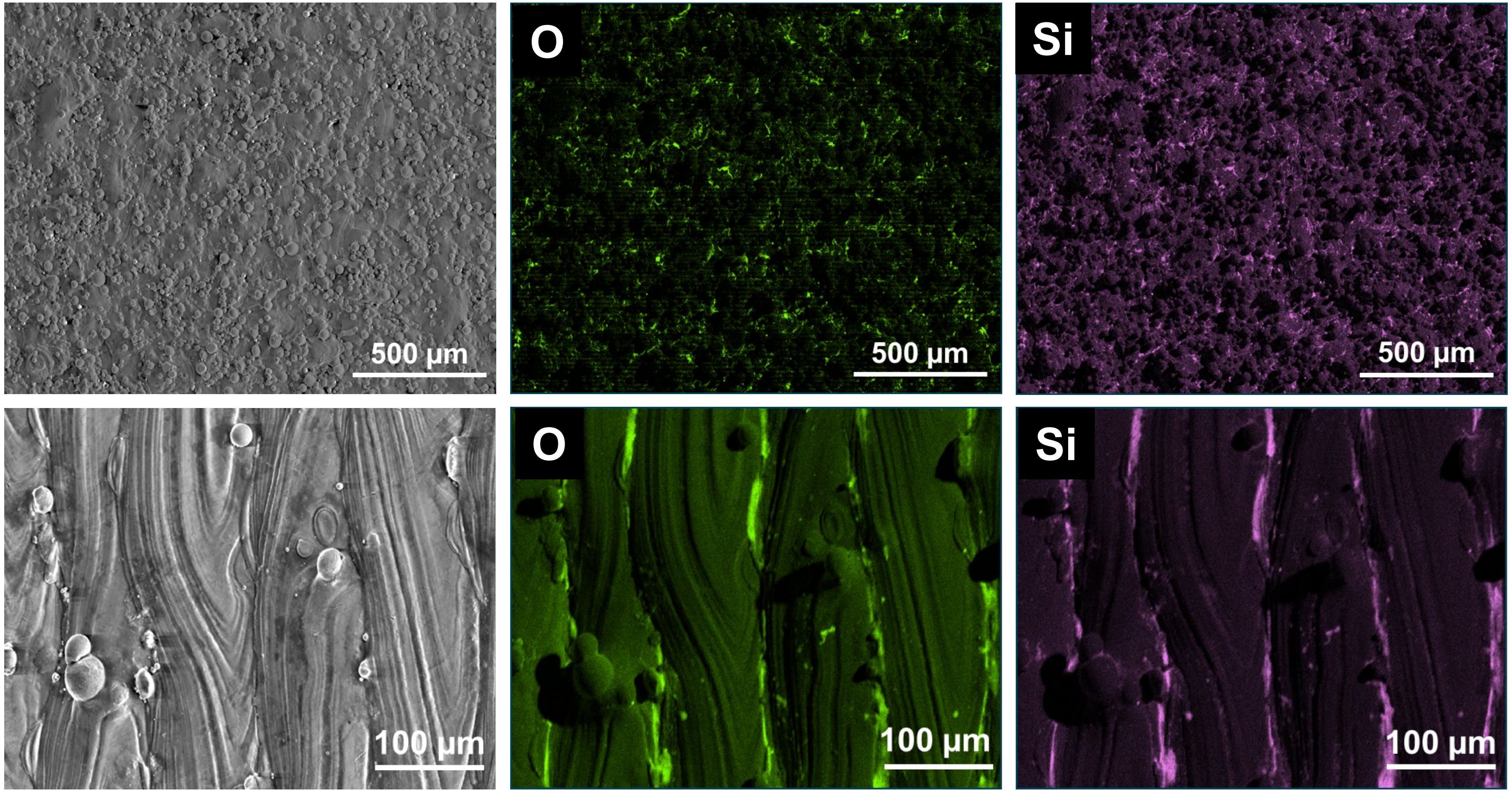
Grain boundary attack and salt infiltration - mechanistic insight

Active research is building understanding of molten salt corrosion from engineering alloys to fundamental mechanisms, predominantly on polished surfaces

The as - deposited AM surface - what it looks like

Side Surface

Top Surface



Oxy-silicate deposits - randomly distributed

Slag along weld pool boundaries - O and Si rich

These surface features may influence how and where corrosion initiates on as-deposited AM components

Corrosion in as - deposited AM - a proposed framework

STAGE 1

Initiation
Governed by surface condition - salt first contacts the as-deposited surface

- **Slag / oxy silicates**
- **Surface roughness**
- **Wetting behavior**
- **Oxide layer**

Largely absent in polished surface studies

STAGE 2

Propagation
Governed by microstructure - corrosion penetrates through material pathways

- **Grain boundaries**
- **Porosity**
- **Secondary Phases**
- **Anisotropy**

Well, represented in current literature

Both stages need to be understood for qualification - this framework motivates our ongoing work on as-deposited AM corrosion

Experimental approach - this work

Material

AM 316H Stainless Steel

Laser powder bed fusion LPBF

Build Direction: Vertical

Solution Annealing: 1050 °C, 30 mins, WQ

Surface Conditions

As-deposited

Surface intact - roughness, slag, oxy-silicates present

Vs.

Machine-cut

Controlled surface - process artifacts removed

Corrosion Environment

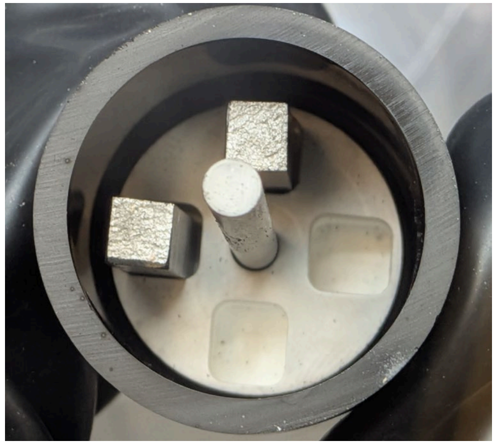
Purified chloride salt ($NaCl$-$MgCl_2$)

Commercial salt from **TerraPower** - purified to control salt chemistry variables

Salt purity controlled - isolating material and surface effects

650 °C, 350 hrs.

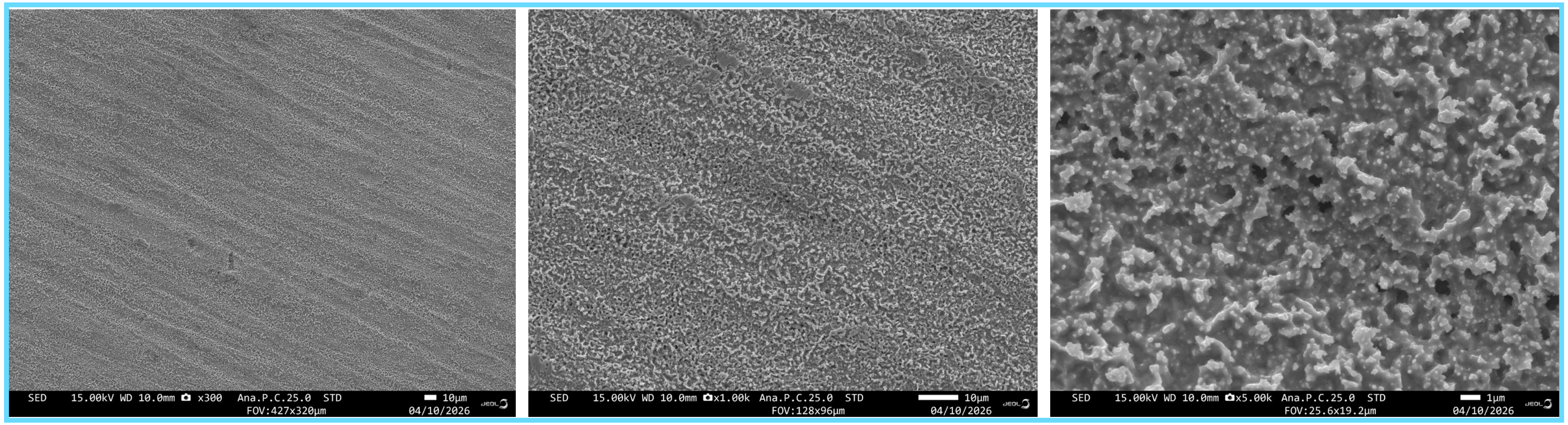
Experimental Setup



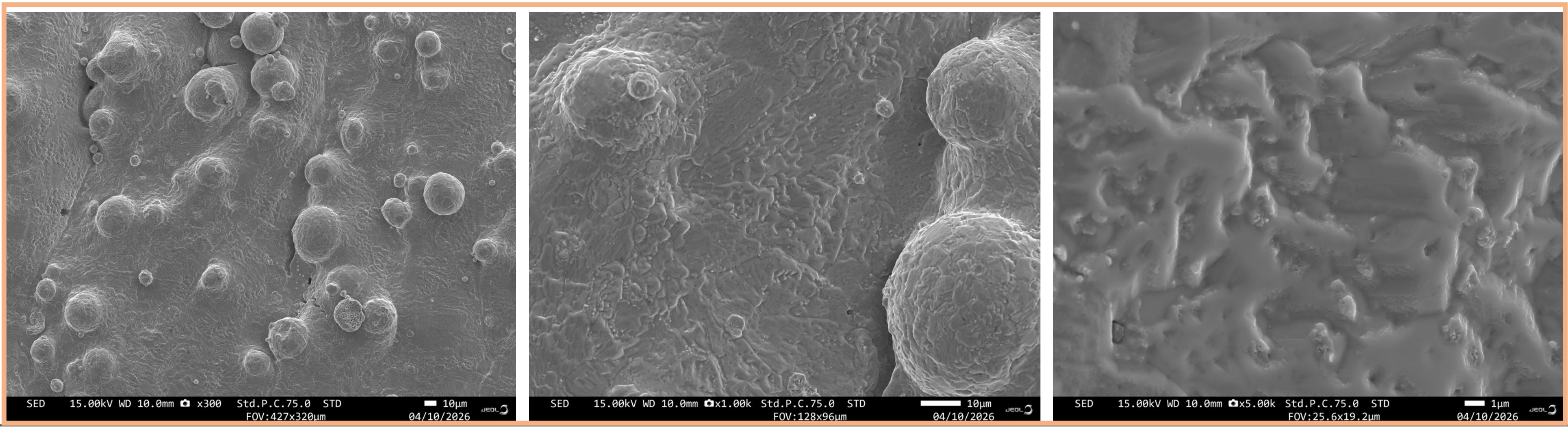
Two surface conditions - same material, same environment - designed to isolate the role of surface condition in corrosion response

Post-corrosion surface morphology - as-deposited vs. machine-cut

Machine cut Surface

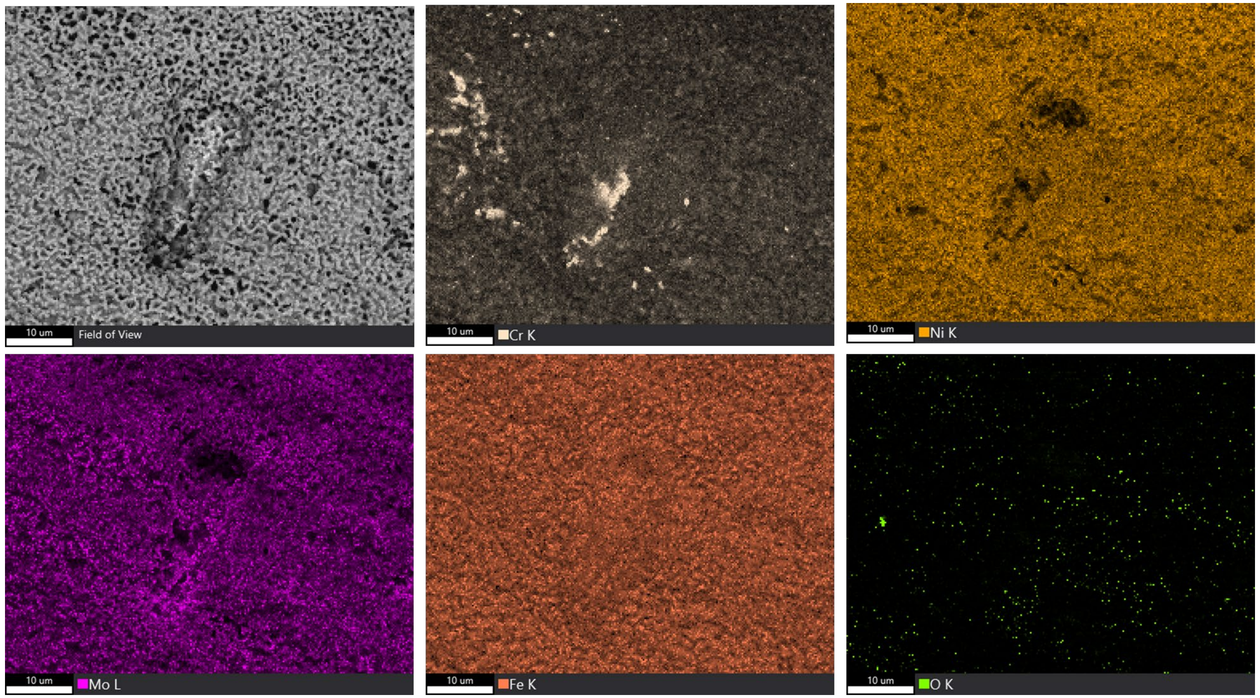


As-Deposited Surface



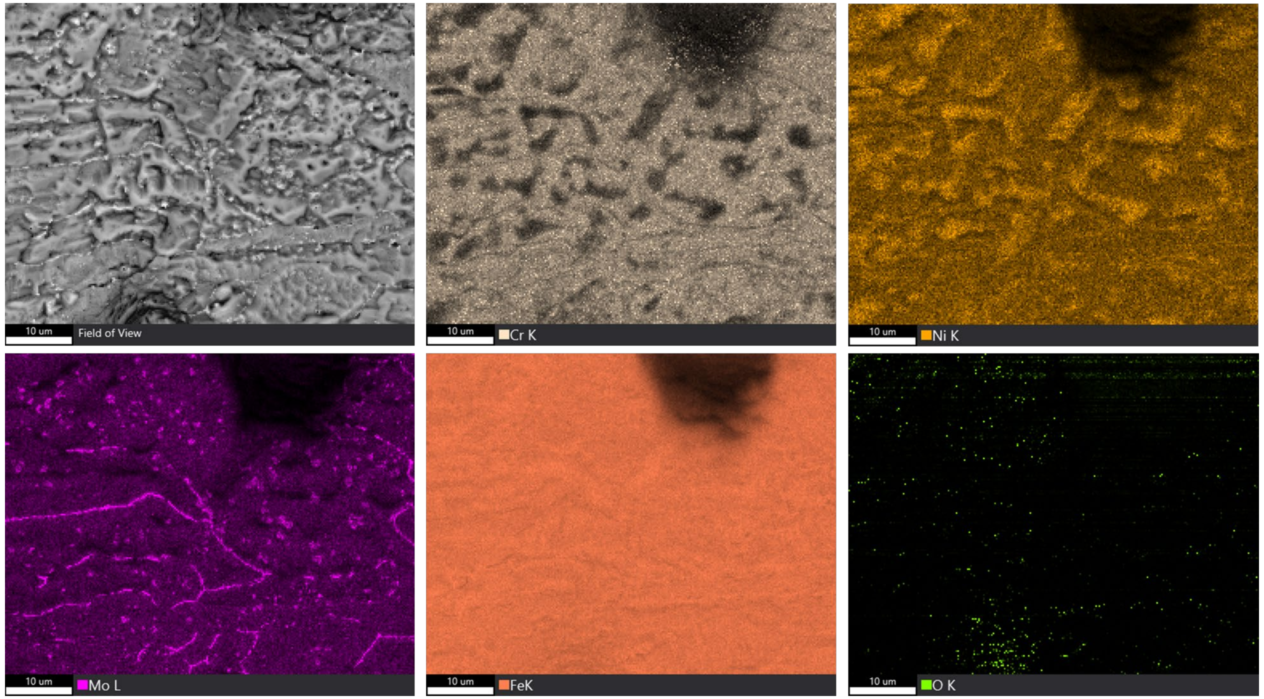
Post-corrosion EDS analysis - elemental redistribution comparison

Machine Cut Surface



Uniform Cr depletion and Ni enrichment - homogeneous corrosion response

As-Deposited Surface

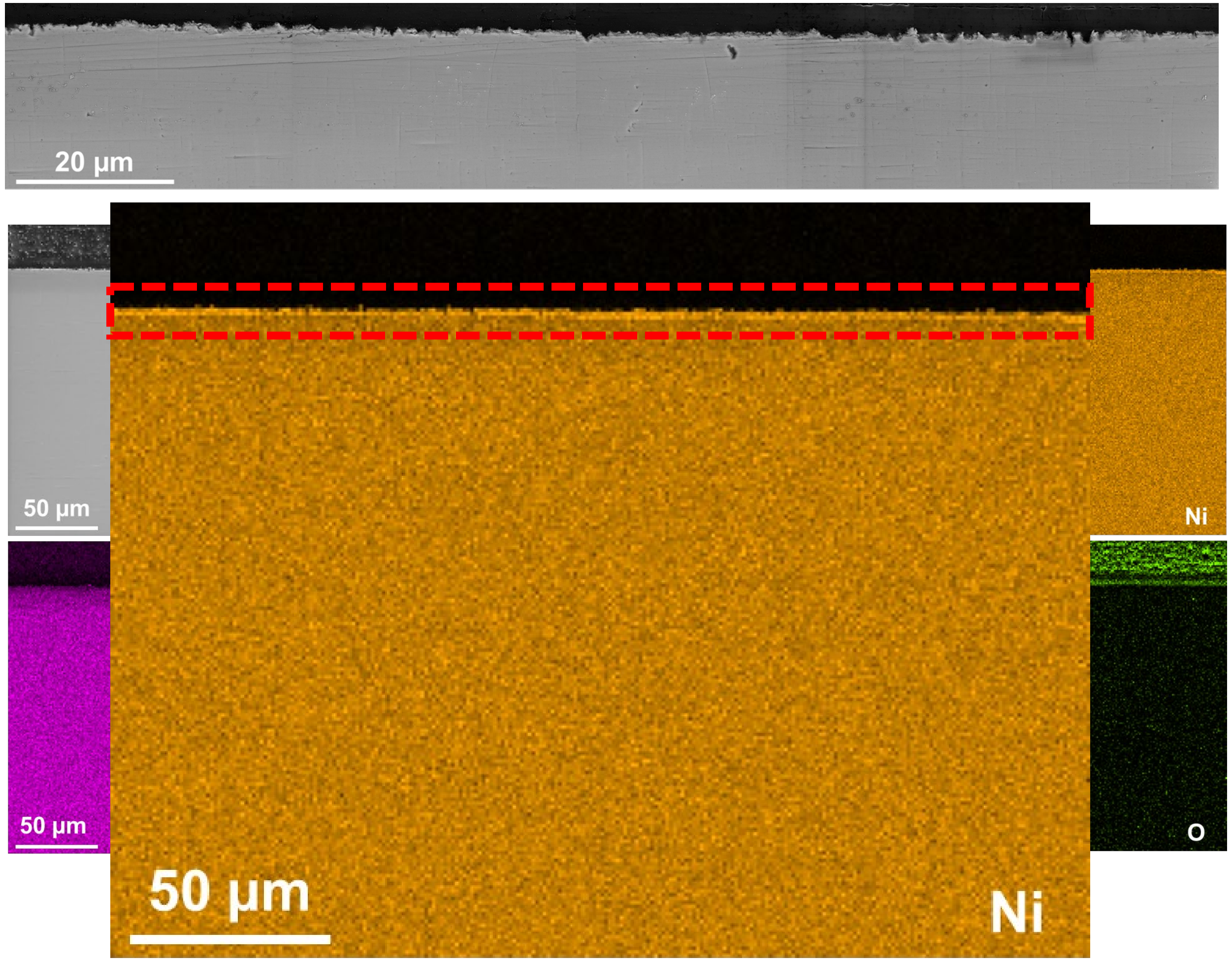


Patchy Cr depletion, localized Ni enrichment and Mo-rich channel features

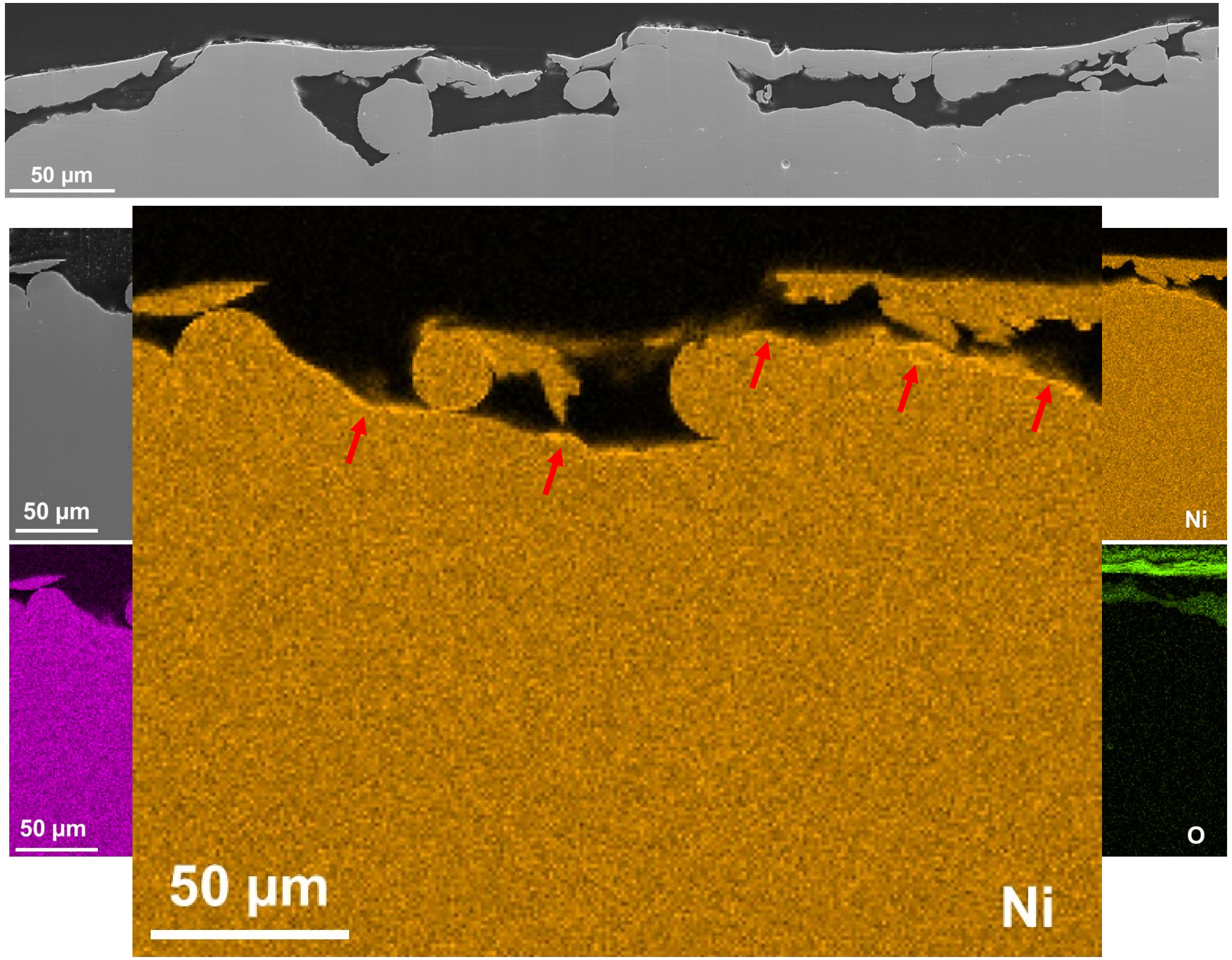
As-deposited and machine-cut surfaces show fundamentally different elemental redistribution - surface condition governs corrosion response in AM 316H

Post-corrosion EDS analysis - elemental redistribution comparison

Machine Cut Surface



As-Deposited Surface



Summary

- AM introduces **complex surface and microstructural features** - both govern corrosion in molten salt.
- As-deposited and machine-cut surfaces show **fundamentally different corrosion** morphology and elemental redistribution.
- Preliminary results consistent with a **two-stage process** - surface governs initiation, microstructure governs propagation.
- Corrosion of as-deposited AM materials is an **open and important consideration for qualification**.

Polished surface studies are essential but as-deposited condition must also be considered for qualification

Ongoing and future work

STATIC IMMERSION

Long-duration exposure - capturing Stage 2

1000 hrs. testing for as-deposited vs machine-cut in molten chloride salt

FLOW LOOP

Dynamic conditions - service-representative

Corrosion under flowing salt - wetting and mass transport effects

Ruchi – Subsequent talk

WROUGHT COMPARISON

AM vs wrought - establishing the baseline

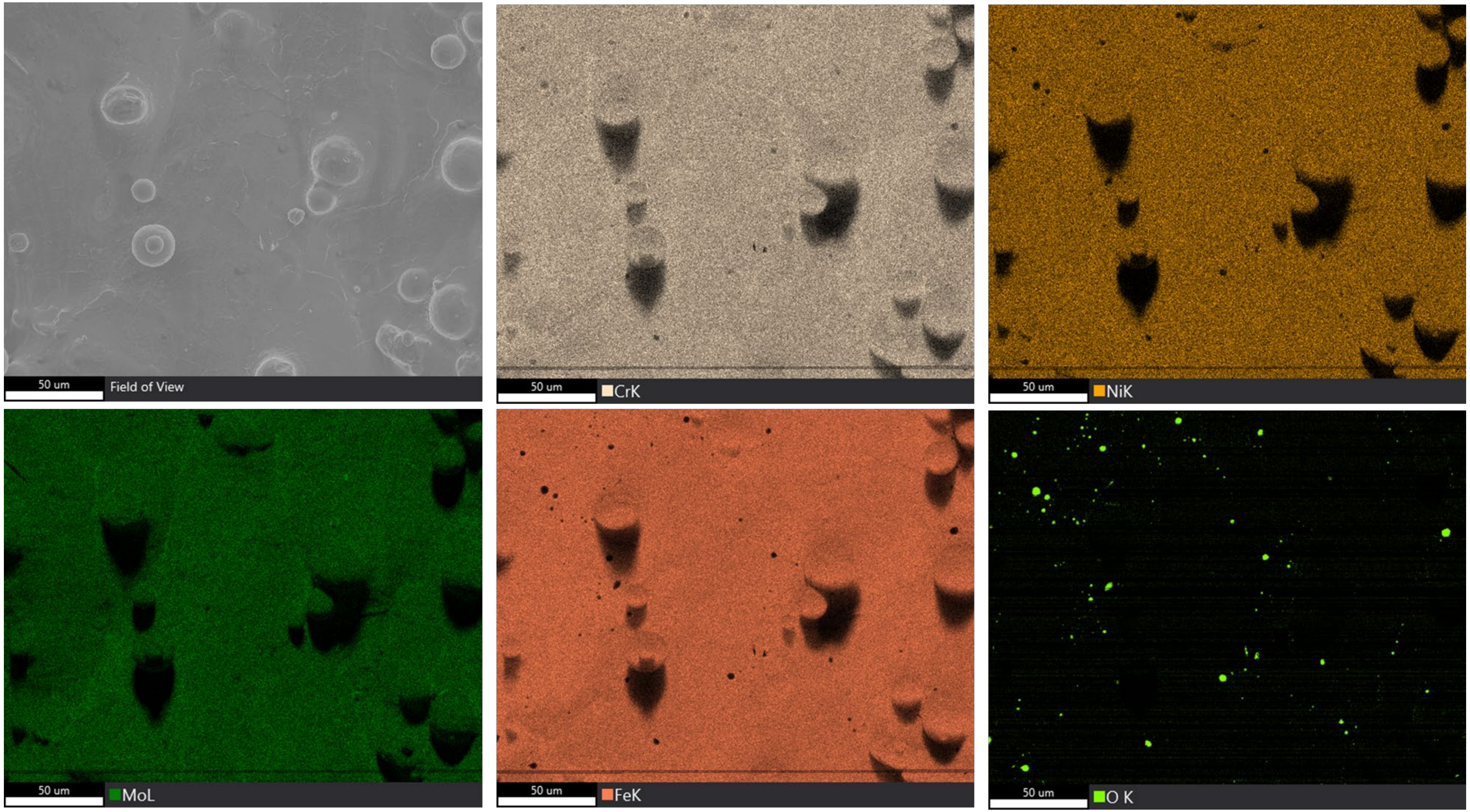
How does AM corrosion behavior compare to conventional wrought material

Together these efforts build toward a corrosion assessment framework for AM materials in molten salt service

U.S. DEPARTMENT of ENERGY | Office of Nuclear Energy

Thank You

Pre - corrosion EDS analysis – (AM As –Deposited)



Post - corrosion EDS analysis – (AM As – Deposited)