SAND2020-9742C

C06-1307: Effects of Applied Stress on Atmospheric Corrosion and Pitting Characteristics of 304 Stainless Steel

PRiME 2020
October 5th 2020

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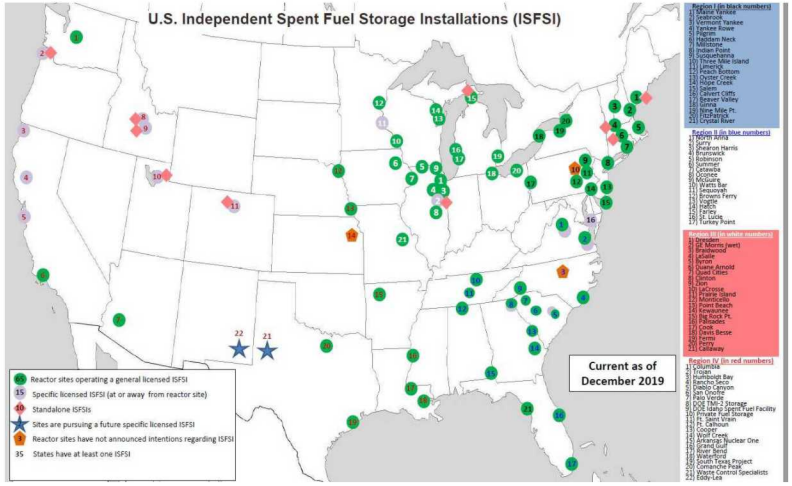
Motivation

Accumulation of spent nuclear fuel cannisters (SNF)

- 80 sites in 35 states
- Austenitic stainless steel (SS)
- Located in/near marine locations
- Salts can deliquesce on surface leading to corrosive environment
- Susceptible to pitting and subsequent stress corrosion cracking (SCC)



https://www.nrc.gov/docs/ML1933/ML19337C178.pdf

https://blogs-images.forbes.com/jamesconca/files/2018/03/ENW-Dry-Cask-figure.jpg

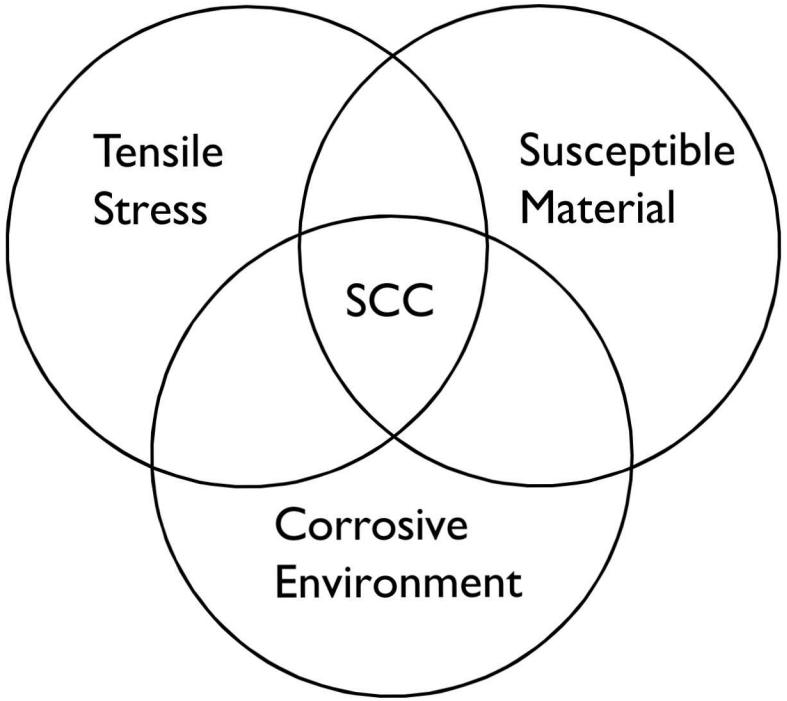
Motivation

Remains a challenge to predict pitting and possible SCC

- **Unknown effects of stress on corrosion and SCC due to canister formation and welding**

Stress Corrosion Cracking from Atmospheric Exposure

Both corrosion and tensile stress, be it applied or residual, are required for SCC to occur



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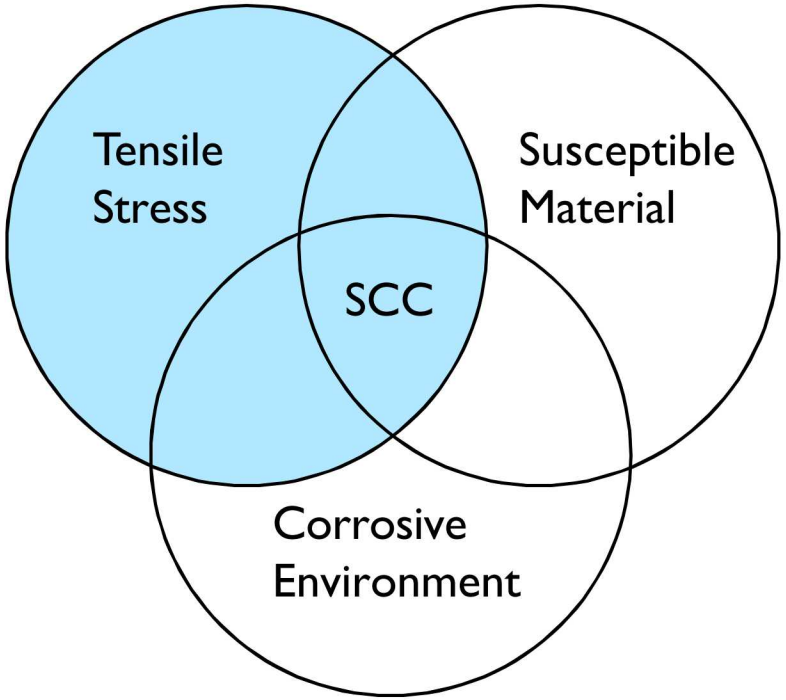
Stress Corrosion Cracking from Atmospheric Exposure

Both corrosion and tensile stress, be it applied or residual, are required for SCC to occur

Factors that govern SCC susceptibility

- **Magnitude of applied stress**



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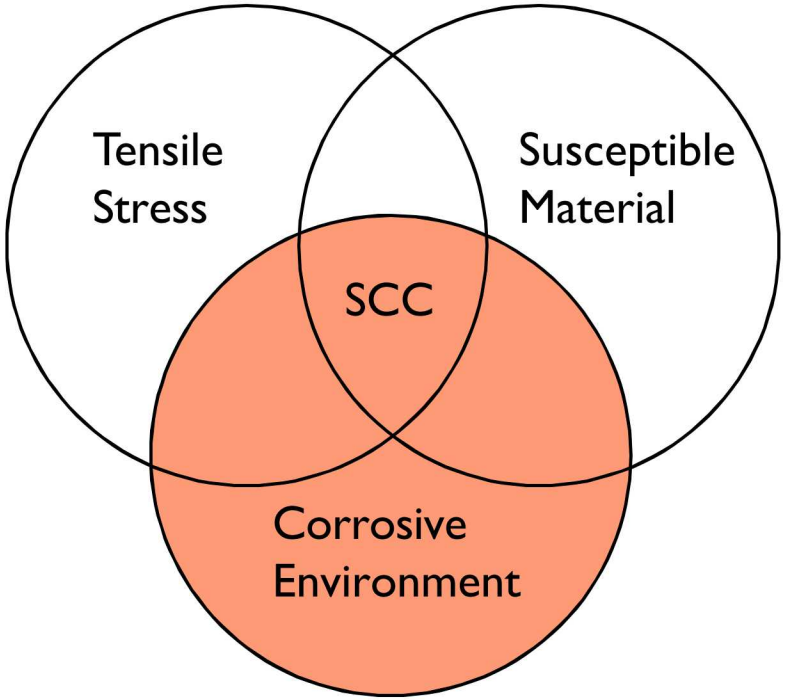
*D.T. Spencer, M.R. Edwards, M.R. Wenman, C. Tsitsios, G.G. Scatigno, P.R. Chard-Tuckey, *Corros. Sci.* 88 (2014): p. 76-88

Stress Corrosion Cracking from Atmospheric Exposure

Both corrosion and tensile stress, be it applied or residual, are required for SCC to occur

Factors that govern SCC susceptibility

- **Magnitude of applied stress**
- **%RH**
- **Salt Loading**



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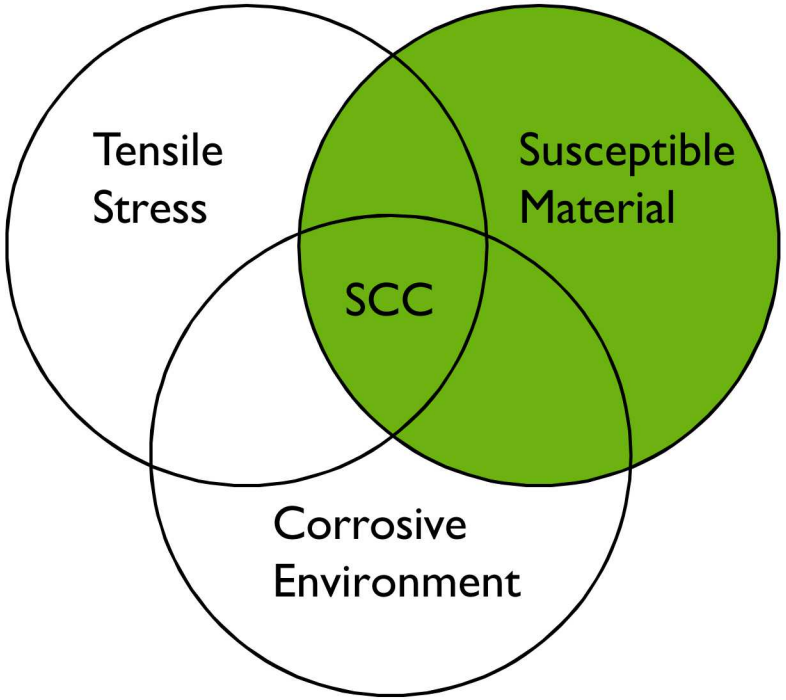
** G.G. Scatigno, P. Dong, M.P. Ryan, and M.R. Wenman, *Mater.* 8 (2019): p. 100509

Stress Corrosion Cracking from Atmospheric Exposure

Both corrosion and tensile stress, be it applied or residual, are required for SCC to occur

Factors that govern SCC susceptibility

- **Magnitude of applied stress**
- **%RH**
- **Salt Loading**
- **Phase composition**



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** G.G. Scatigno, P. Dong, M.P. Ryan, and M.R. Wenman, *Mater.* 8 (2019): p. 100509
*** C. Örnek, X. Zhong, and D. L. Engelberg, *CORROSION*. 72, 3 (2016): p. 384-399

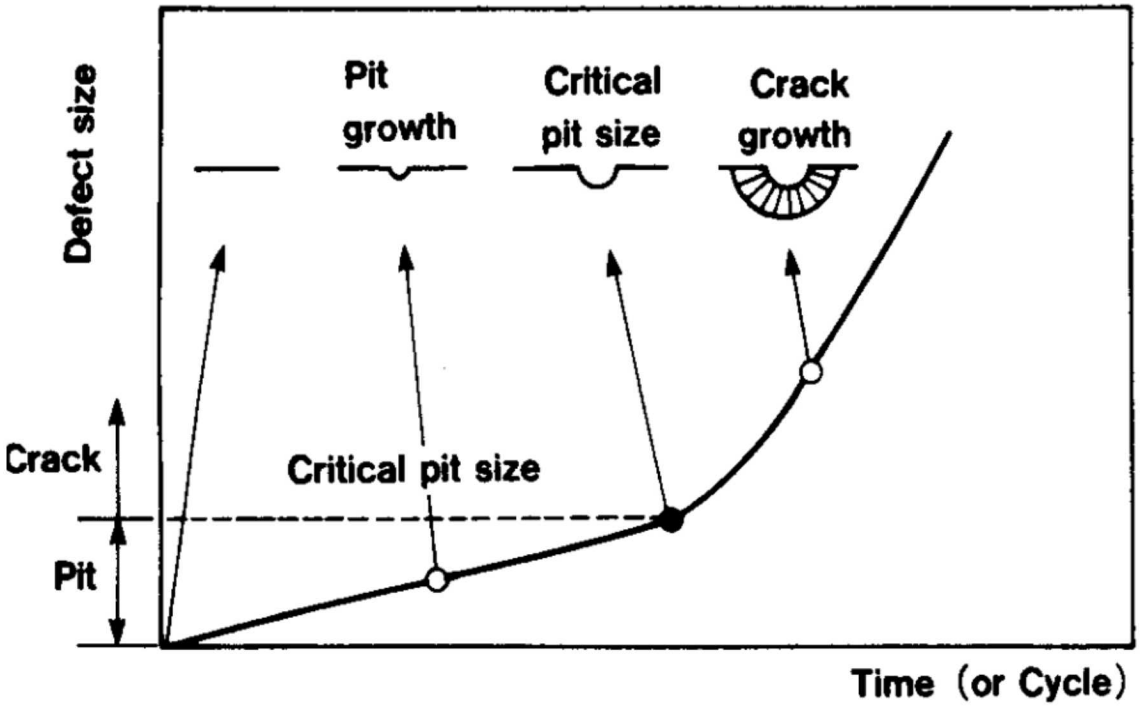
Pit to Crack Transition

Pit to crack criteria proposed by Kondo*

- Pit depth > threshold depth
- Crack growth rate > pit growth rate

Applied stress can increase pitting susceptibility

- Higher pitting density and higher probability of deeper pits
  - More cracking



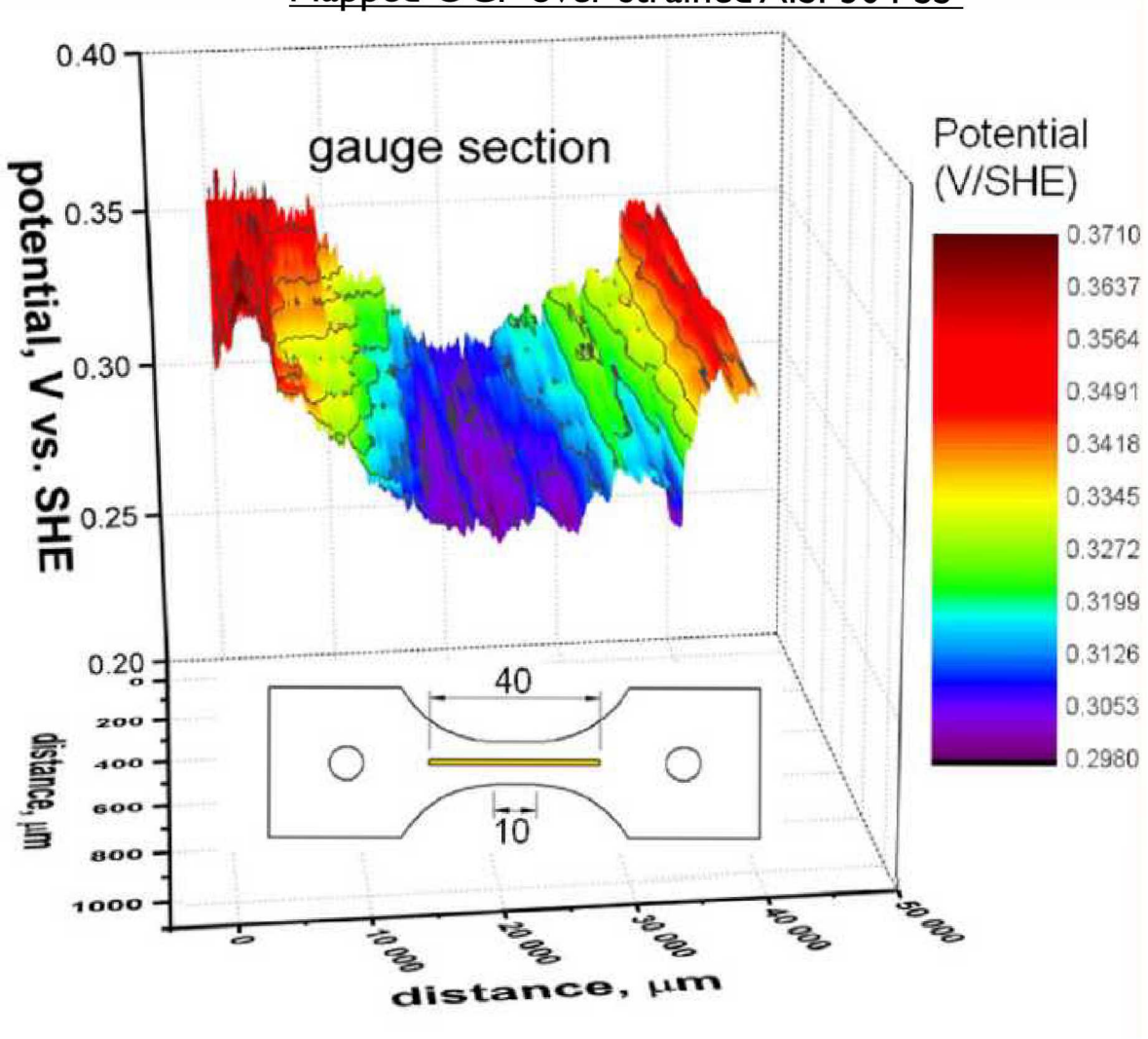
*Y. Kondo, Corrosion, 45, 1 (1987): p. 7-11.

Influence of Stress on Corrosion

Stress causes the material to have lower open circuit potential (OCP)

Lower OCP signifies a greater corrosion susceptibility

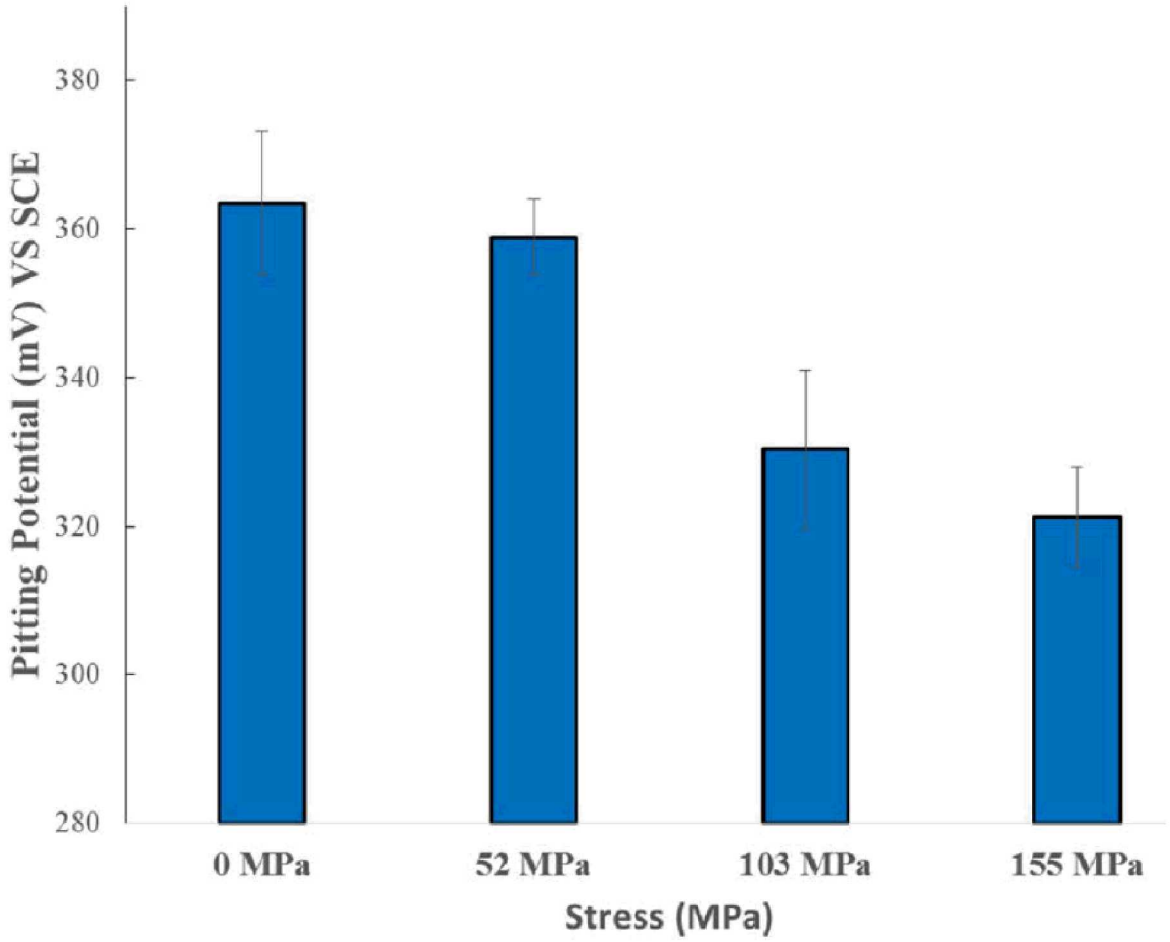
Mapped OCP over strained AISI 304 SS



A. Nazarov, V. Vivier, F. Vucko, and D. Thierry, *J. Electrochem. Soc.* 166, 11 (2019): p. C3207-C3219

Influence of Stress on Corrosion

More corrosion susceptibility at higher stress



G. Wu and P.M. Singh, *J. Electrochem. Soc.*, 166, 8 (2019): p. C209-C216

Research Questions

It's been observed that stress has an effect on pitting, what about in canister relevant environments…

- Under atmospheric exposure what dependence does stress have on pit distribution, pit size, and pit morphology in 304L SS?
- What are some of the more localized effects stress can have on pitting?

Experimental Approach

Applied stress to 304L SS bar using 4 pt. bend
- Finite element analysis (FEA)
- Direct image correlation (DIC)

Polished (0.1 Ra μm)

Artificial seawater (ASW) Loading density (4 g/m^2 chloride)

Atmospheric exposure in humidity chamber (50 days at 50 °C and 35 % RH)
- Accelerated corrosion
- Cleaning Procedure (submerged in 0.6 M diammonium citrate solution at 70 °C for 24 hours (ASTM-G1))

Analysis

Optical profilometry
- Pitting analysis

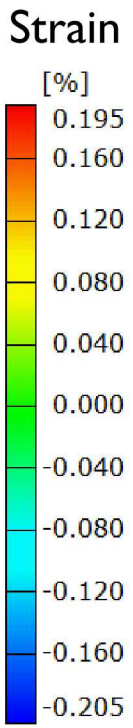
Scanning electron microscopy (SEM)
- Interrogate pits further

Electron backscatter diffraction (EBSD)
- Composition analysis

Micro-electrochemical cell
- On unexposed 4-pt bend bar
- Localized electrochemical parameters

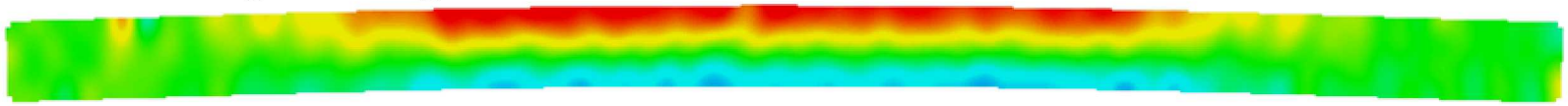
Material and Stress Application

A four-point bend bar was atmospherically exposed to explore a full stress gradient, from tensile to compressive stresses, across the thickness of the bar



Stressed, Corroded 304L Stainless Steel

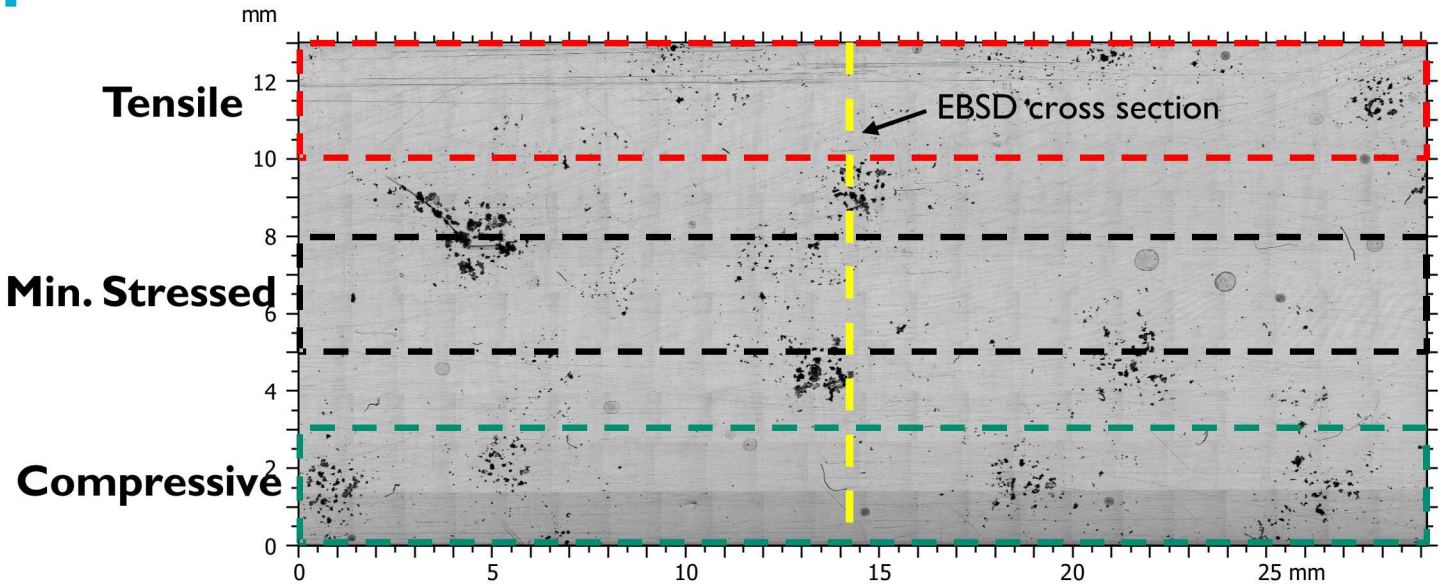
Digital Image Correlation

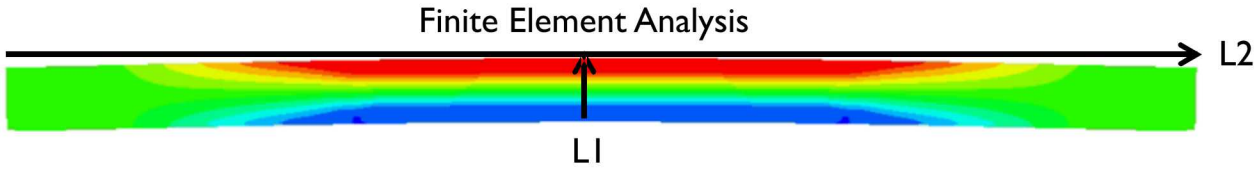


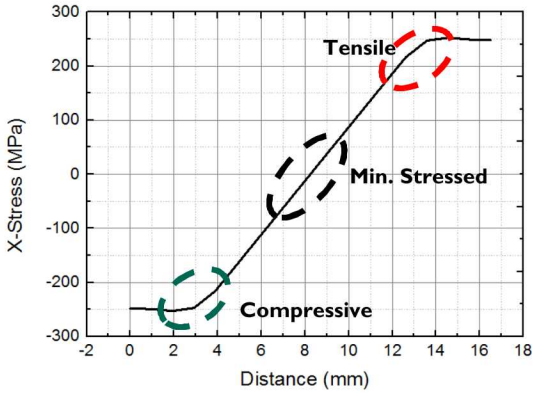
Base metal composition of the 304L stainless steel bar

SS304L bar composition (wt. %)											
C	Co	Cr	Cu	Mn	Mo	N	Ni	P	S	Si	Fe
0.0216	0.198	18.3	0.392	1.83	0.286	0.0889	8.11	0.325	0.001	0.251	Bal.

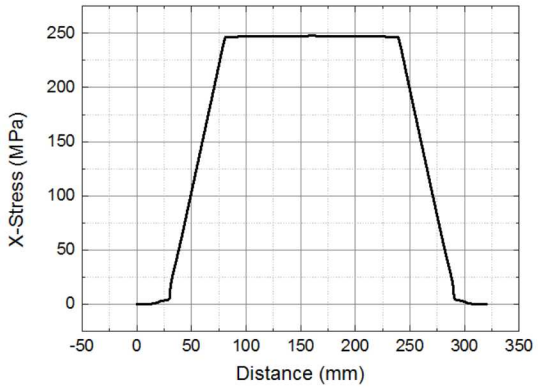
Optical Profilometry







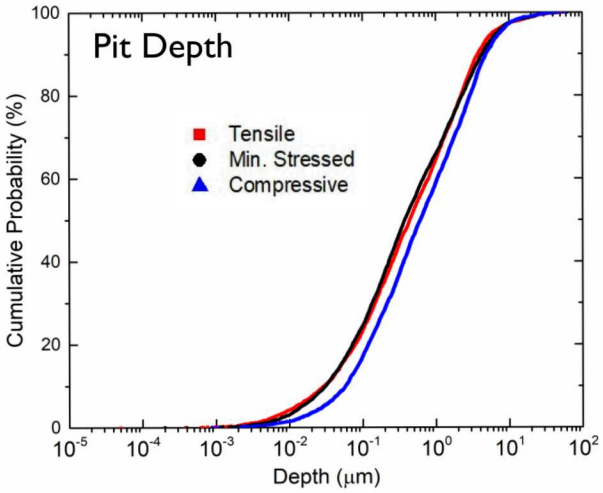
Stress distribution profile along path L1

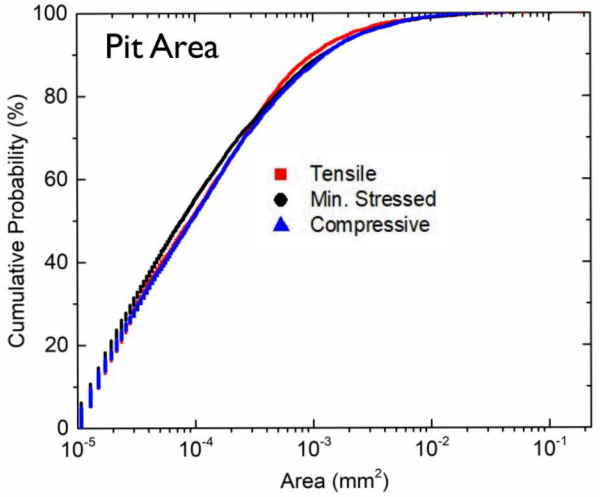


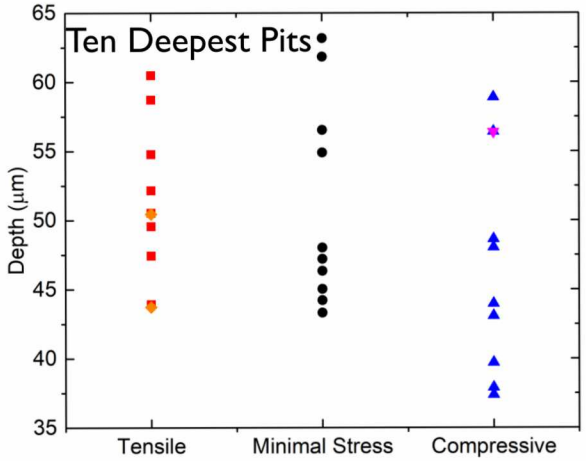
Stress distribution profile along path L2

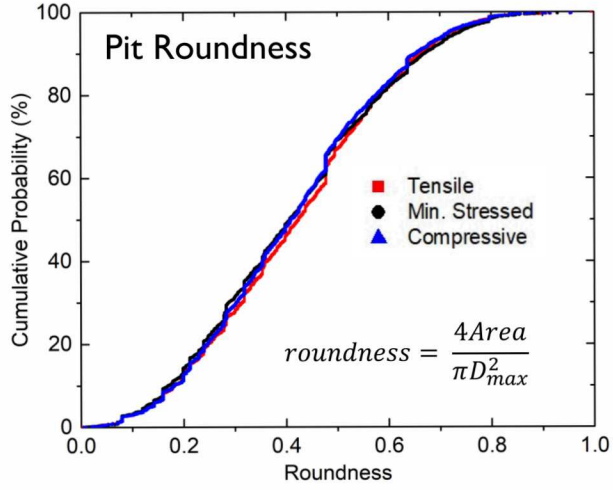
Analysis From Optical Profilometry Measurements

- **No apparent contribution from stress on physical pitting characteristics**



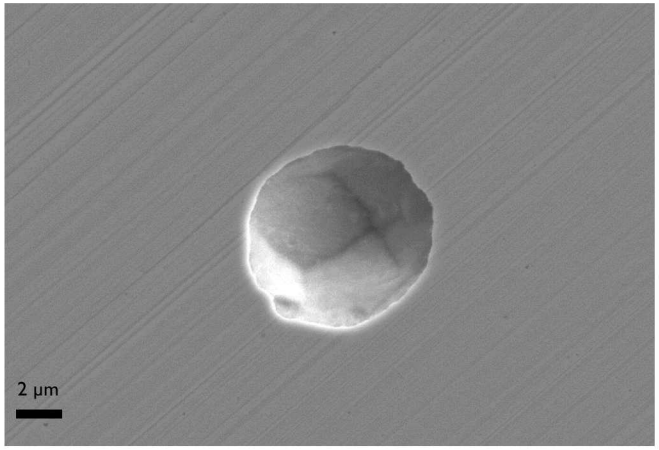




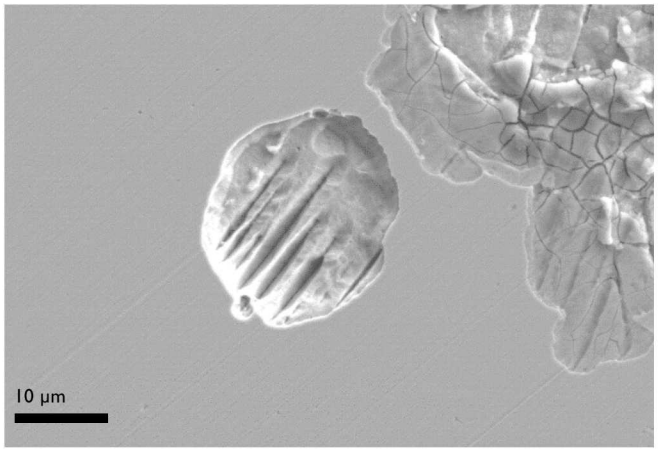


Pitting Density:
Tensile: 1020 pits/cm^2
Min. Stressed: 1270 pits/cm^2
Compressive: 1020 pits/cm^2

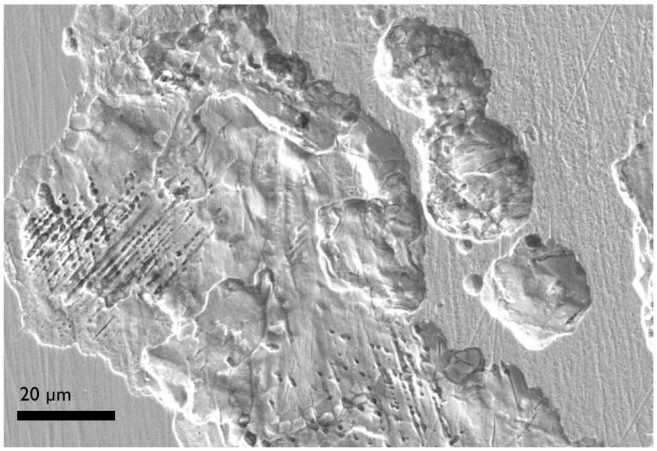
SEM Images (Four Prominent Pit Types)



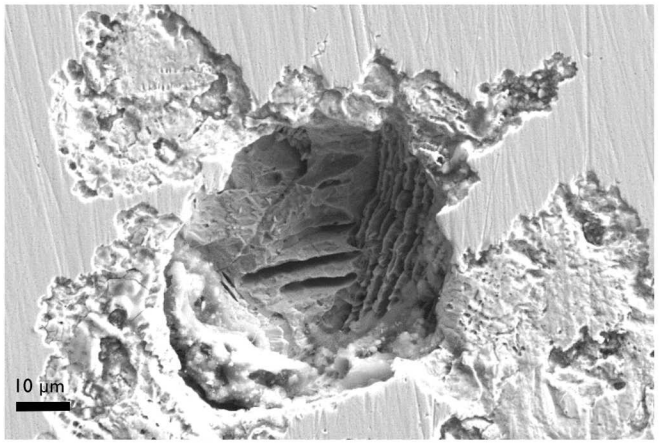
Hemispherical with smooth interior



Hemispherical with interior microstructural attack

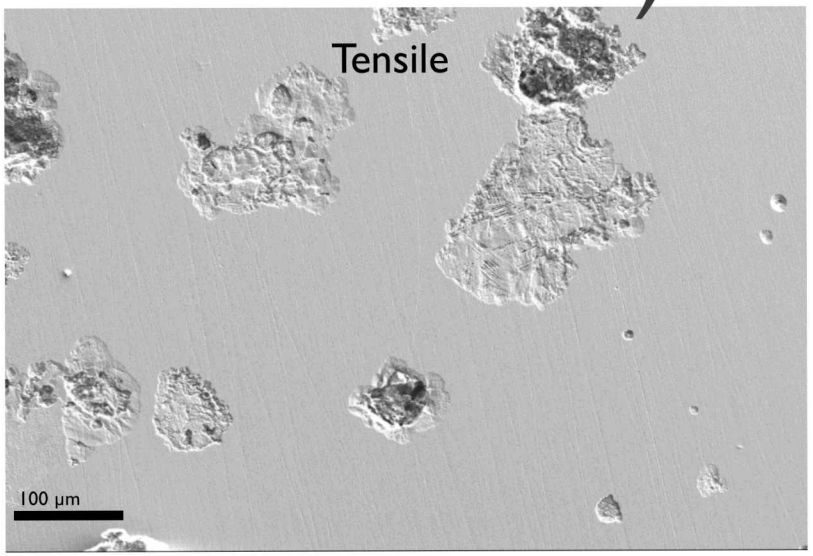


Irregular shaped with shallow microstructural attack

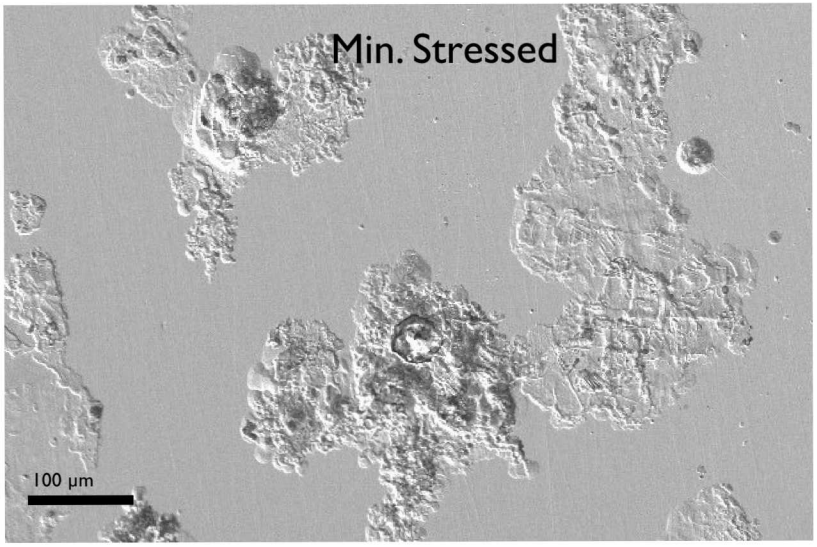


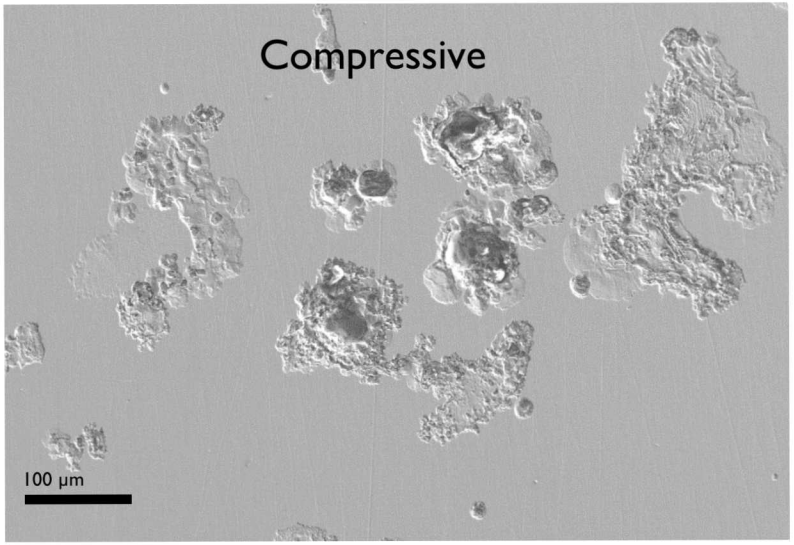
Irregular shaped with deep microstructural attack

Low Magnification SEM (Pitting Distribution)

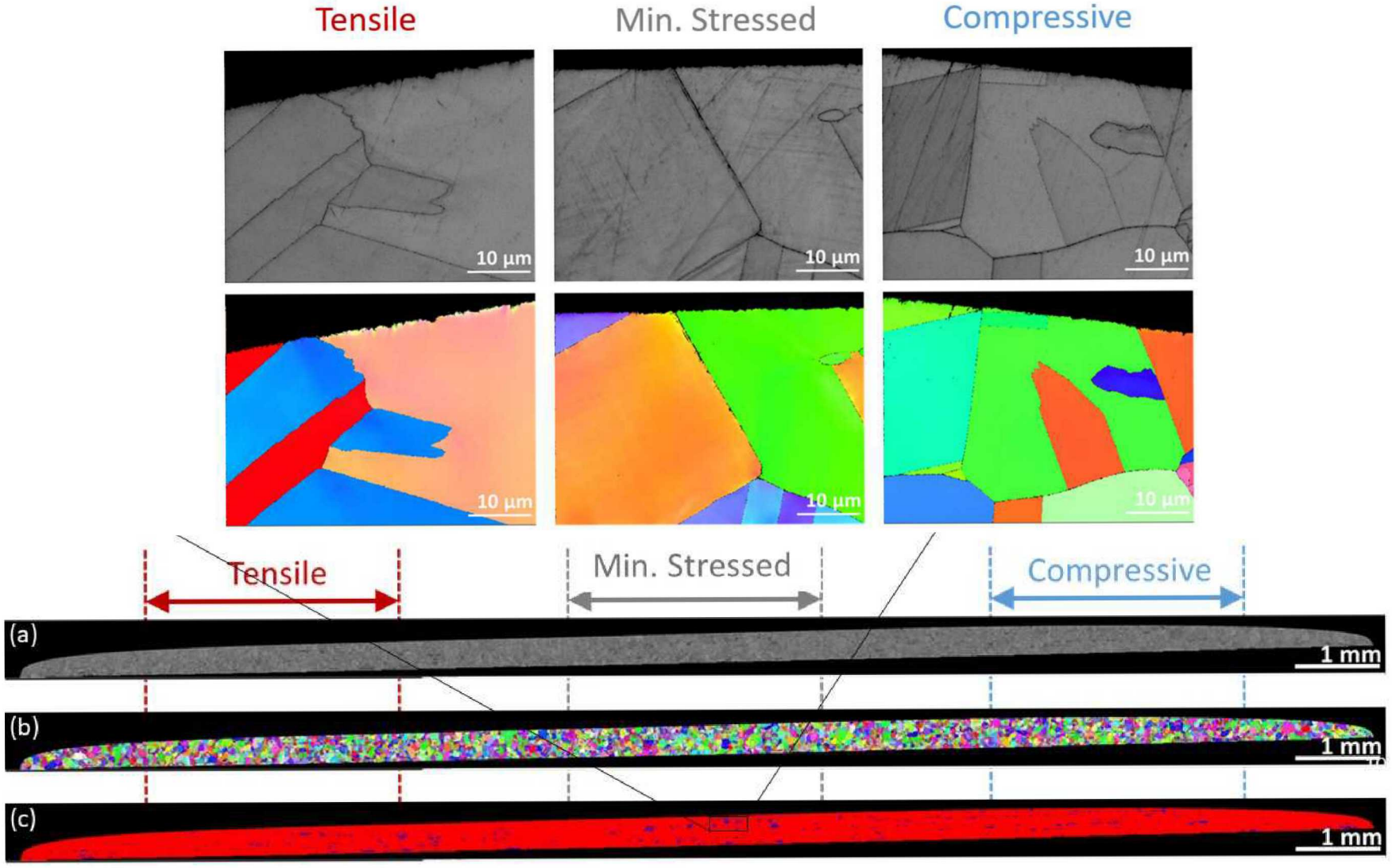


- No obvious effect from stress
- Pitting distribution appears random
- Mixture of hemispherical and irregular pits





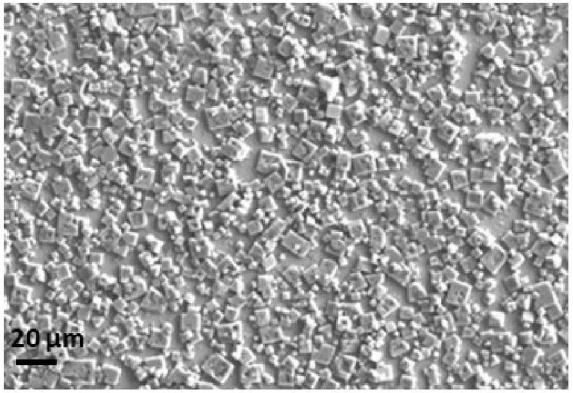
Microstructural characterization Electron Backscatter Diffraction (EBSD)

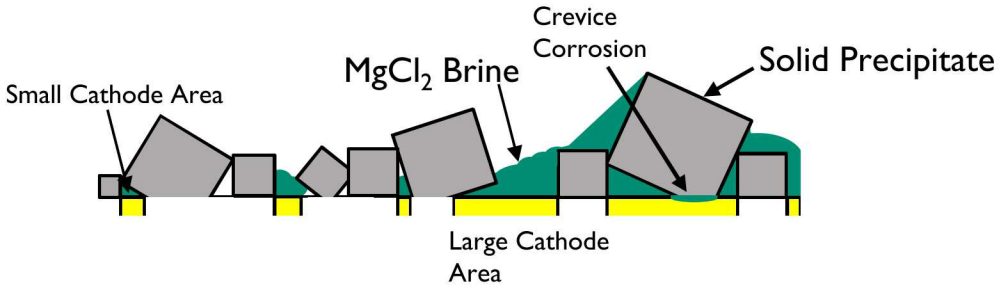


Pitting Morphology and Distribution

Electrolyte, exposure environment, and the underlying material play a role in the pit size and morphology

- Maximum pit size is governed by the electrolyte rather than stress
  - Pitting is assumed to behave according to Chen-Kelly model*
- Precipitated salts disrupt the continuous brine layer at low 35% RH





1. Larger liquid electrolyte volumes = larger available cathodic area
2. Smaller liquid electrolyte volumes = reduced cathodic current

*Z.Y. Chen and R.G. Kelly, *J. Electrochem. Soc.* 157, 2 (2010): p. C69-C78

Microstructural Attack May be a Function of Pre-Existing Phase Composition

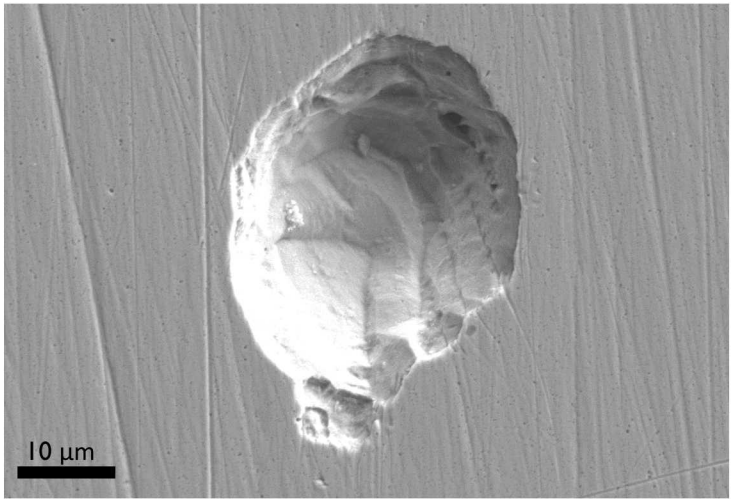
Likely favorable dissolution of martensite within the primary FCC austenitic phase

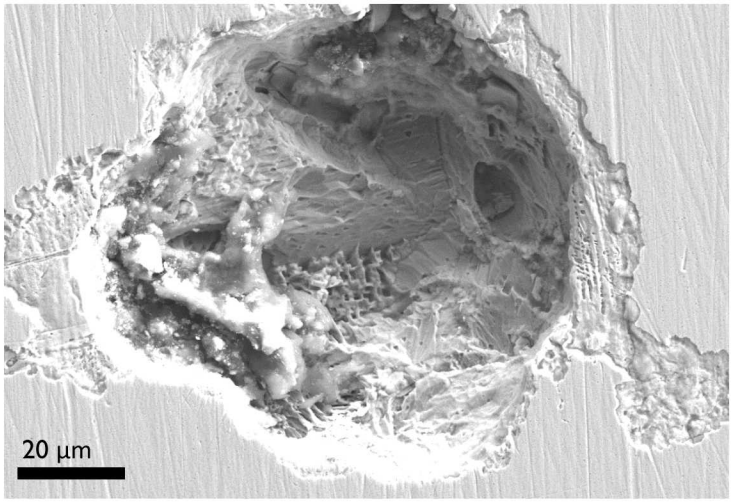
Smooth hemispherical pit

- Sufficient cathode area
  - Enough current to corrode both phases at the same rate

Microstructural Attack

- Less cathode area
- Both phases corroding at different rates





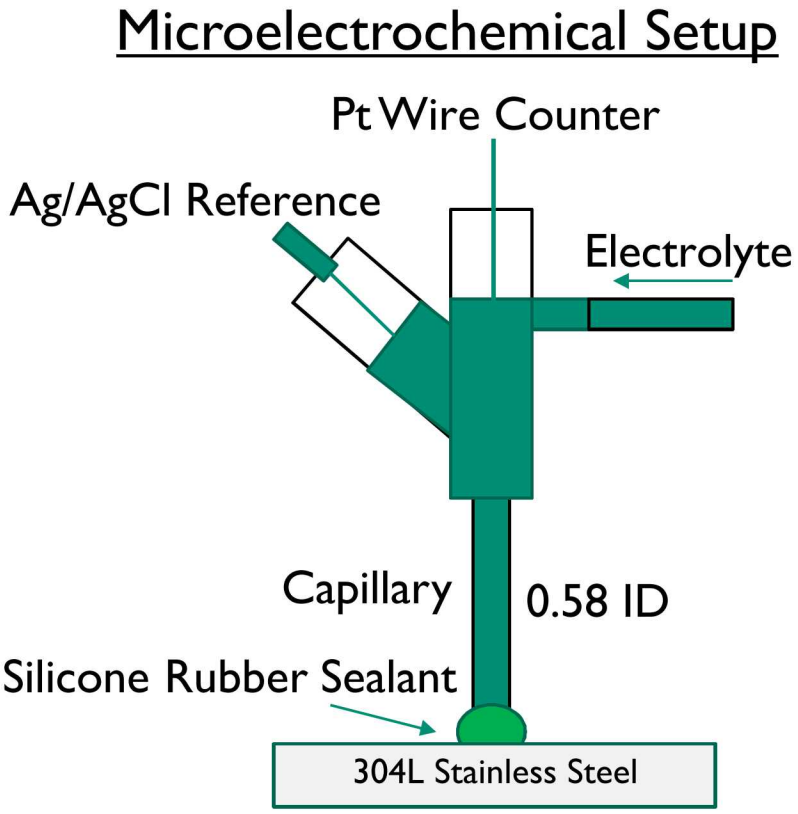
Approach (Microelectrochemical Cell Measurements)

Motivation

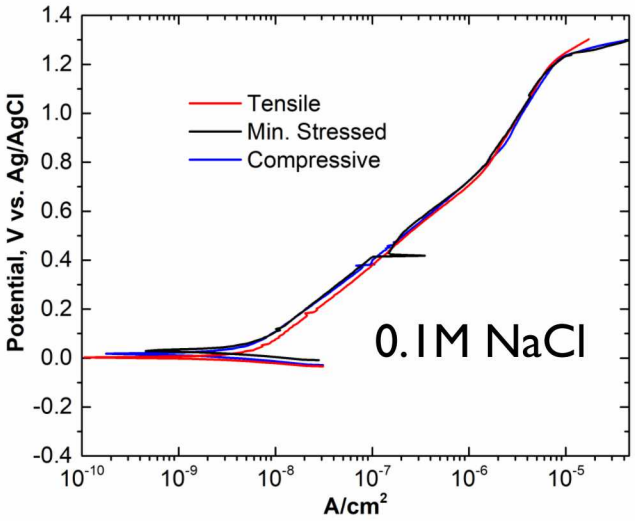
- Believed that aggressive, high chloride environment dominates pitting susceptibility
- Overrules any effects by localized stresses

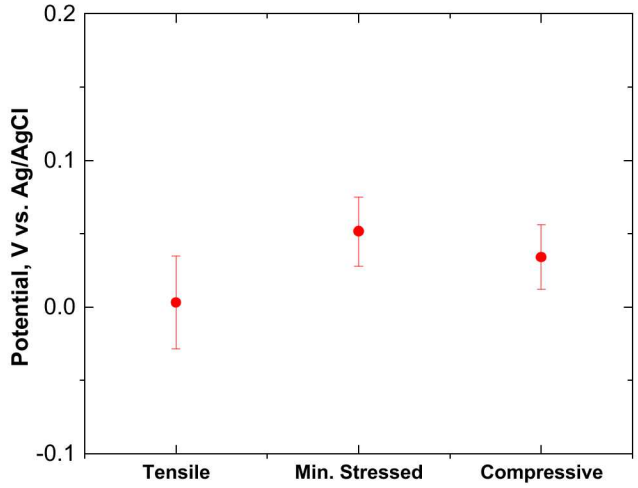
Local, spatially selective electrochemical investigations were carried out in both aggressive and benign chloride solutions

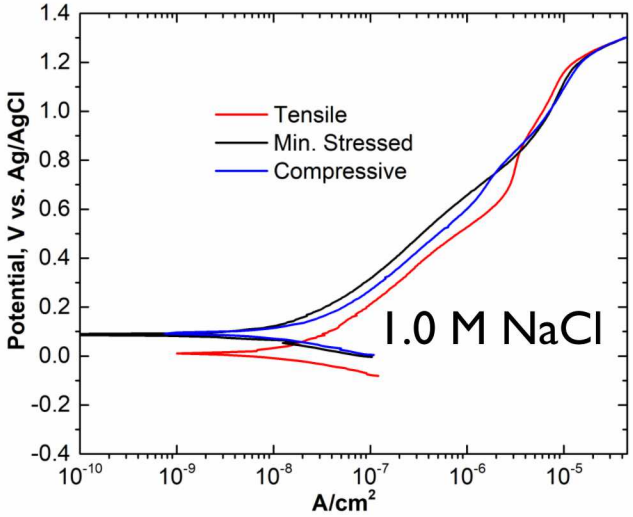
- 0.1 and 1 M NaCl
- 0.05 and 0.5 M $MgCl_2$

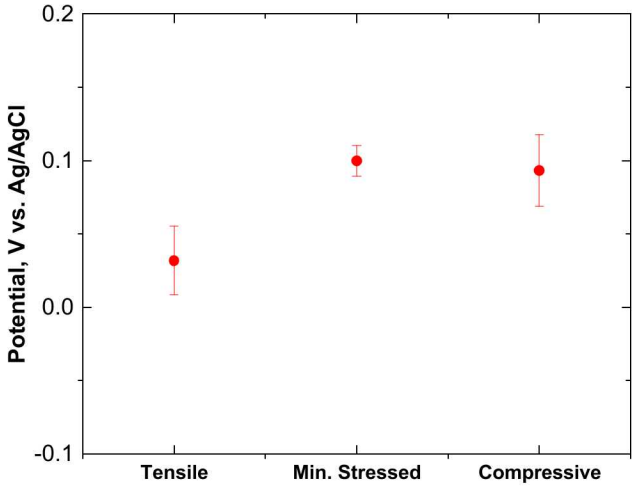


Microelectrochemical Cell Potentiodynamic Scans of Stressed 304L Bar Exposed to NaCl





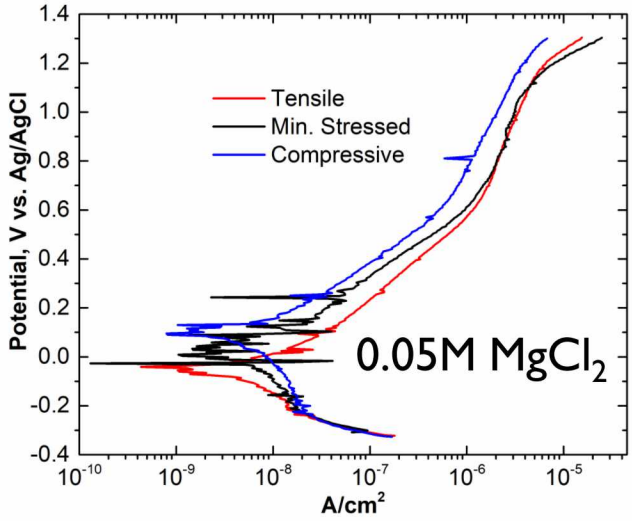


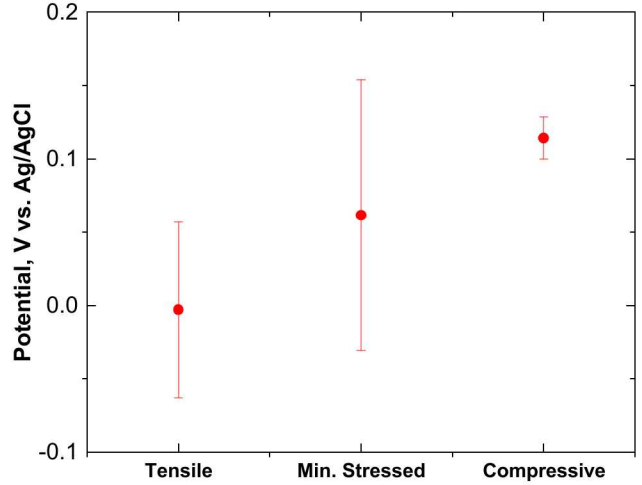


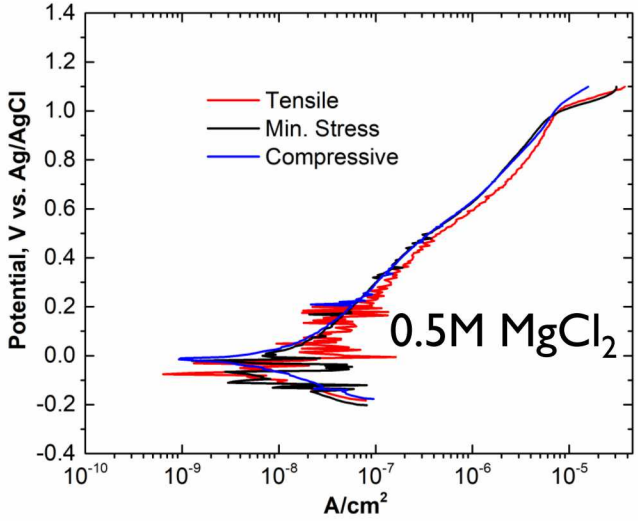
Potentiodynamic Scans

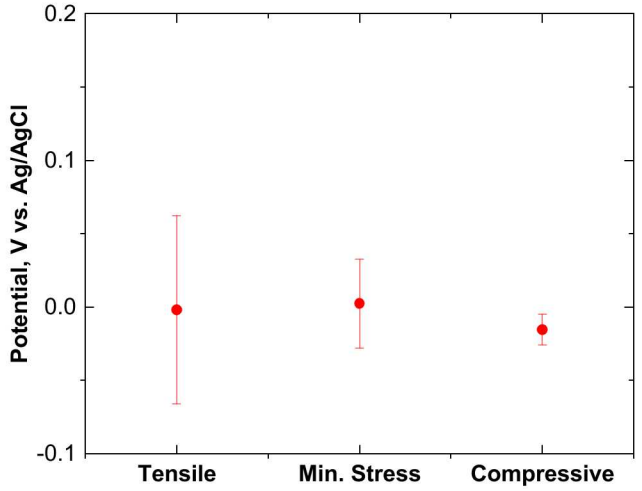
OCP Averaged Over 5 Scans

Microelectrochemical Cell Potentiodynamic Scans of Stressed 304L Bar Exposed to $MgCl_2$









Potentiodynamic Scans

OCP Averaged Over 5 Scans

Conclusions

1) Atmospheric exposure conditions explored herein were highly aggressive
- Dominated effects from applied stress on resultant pit morphology

2) High salt load and low RH resulted in irregularly distributed brine and brine concentration

3) Dominated by
- pre-existing phase composition of the SS
- cathodic availability of the heterogeneous brine
- crevice formation from precipitated salts

4) Effects of applied stress on the electrochemical polarizations were enhanced in more benign (lower chloride concentration) environments

Conclusions and Future Work

- ***Still want to understand:*** What are the mechanisms of pitting under stress and how does pitting initiate cracks during atmospheric exposure?

- ***From current study:*** severity of brine environment played a larger role in governing pit distribution, morphology, and size than applied stress
- ***Future work:*** Determine effects of varied deposition densities, brine concentrations, exposure conditions, etc. in combination with applied stress at various levels on resultant pitting and pit-to-crack transition

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