Effect of AC Interference on the Stress Corrosion Cracking Susceptibility of Low Carbon Steels under Cathodic Protection

PHMSA project # DTPH5615HCAP02
Debrief

Lizeth Sanchez

Advisor: Dr. Hongbo Cong
DEPARTMENT OF CHEMICAL, BIOMOLECULAR AND CORROSION ENGINEERING

The University of Akron
College of Engineering

02/26/2020

CONTENTS

- ❑ **Motivation of the research project**
- ❑ **Research objectives**
- ❑ **Research background on environmental cracking under AC**

- ❑ **Influence of AC on stress corrosion cracking (SCC) in low carbon steels under cathodic protection**
    1. Experimental set-up
    2. Results
    3. Conclusions

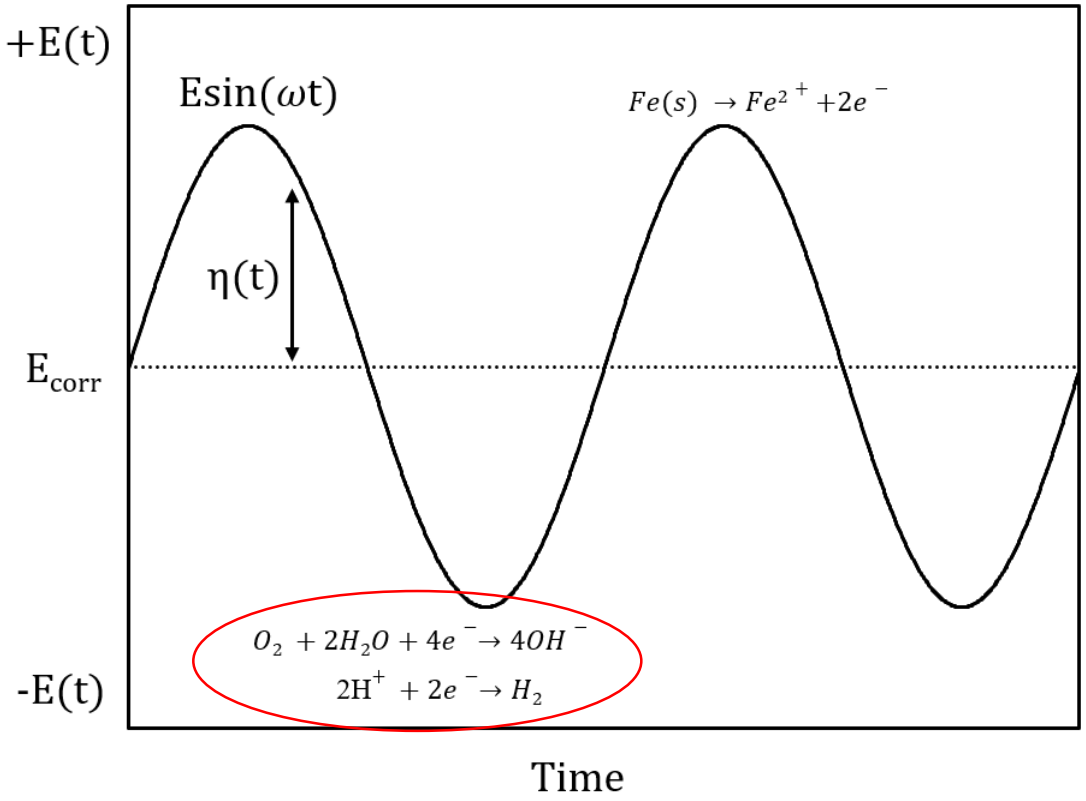
- ❑ **Preliminary pitting study**
- ❑ **Achievements**
- ❑ **Acknowledgement**

WHY IS IMPORTANT TO STUDY FRACTURE SUSCEPTIBILITY UNDER AC ?

- ✓ Due to the overpotentials, AC interference may affect the hydrogen production at the surface. Therefore <u>it can influence the hydrogen uptake</u> on the steel surface which can potentially result in hydrogen embrittlement (increase rates of cathodic reactions).

$$\uparrow i_{H_2} = i_{0H_2} e^{2.3\frac{(-E-0.244)}{\beta_{H_2}}}$$

- ✓ Localized corrosion in the form of pitting has been found on pipelines under the AC interference. <u>SSC cracks may initiate at the pitted sites.</u> Therefore, AC interference may induce or facilitate the occurrence of SCC failures in the steel, which is a significant threat to the pipeline integrity.



OBJECTIVES OF THE PROJECT

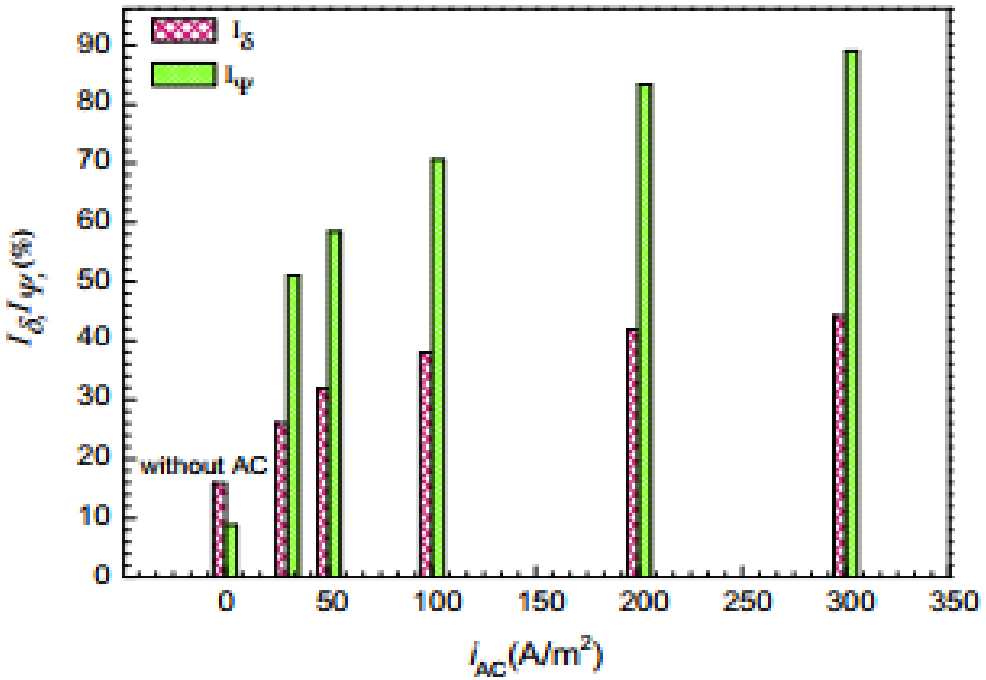
- ✓ Investigate the susceptibility of low carbon steels to environmentally-assisted cracking (EAC) under the combined effect of AC and CP potentials.
- ✓ Evaluate environmental fracture using fracture morphology analysis, tensile and electrochemical tests.
- ✓ Elucidate cracking mechanism under the influence of both AC and CP in low carbon steels.
- ✓ Identify key parameters in the process of AC induced cracking.

RESEARCH BACKGROUND ON AC INDUCED CRACKING

- ✓ Zhu et al. studied the AC effect on the SCC behavior of X80 pipeline steel in bicarbonate solutions.
  - The SCC susceptibility increases as the AC current density increases (30, 50, 100, 200 and 300 A/m^2).
  - The mechanism is attributed to both anodic dissolution and hydrogen embrittlement.

- ✓ Wan et al. found increasing SCC susceptibility (i.e., higher elongation-loss rates) of X80 pipeline steel with higher AC current densities (10, 30 and 50 A/m^2), in near-neutral NS4 solution.

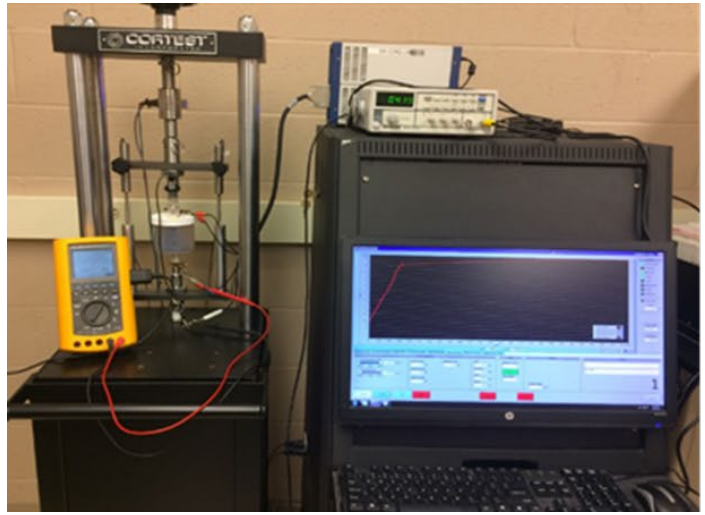
- ✓ Schmitt et al. studied the hydrogen permeation behavior in different solutions under various AC current densities (30 to 500 A/m^2). No clear indications were found if AC can favor hydrogen failure mechanisms.

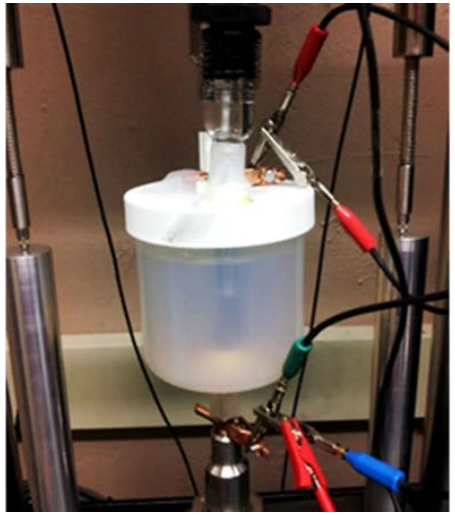


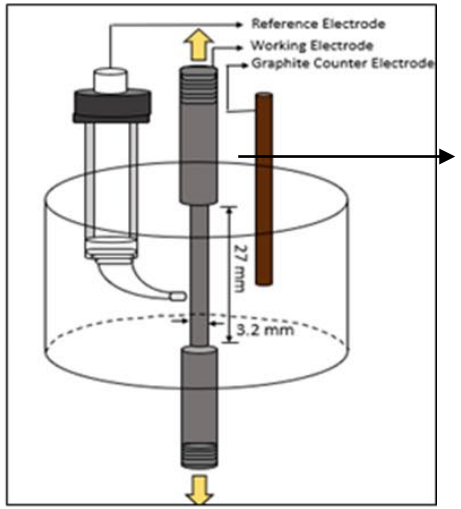
Elongation-loss rate and reduction in area ratio as a function of AC current densities. (Zhu et al. Reference 7)

SUSCEPTIBILITY TO SCC UNDER AC AND DC CONDITIONS- EXPERIMENTAL SET-UP

Slow Strain Rate Test (SSRT)

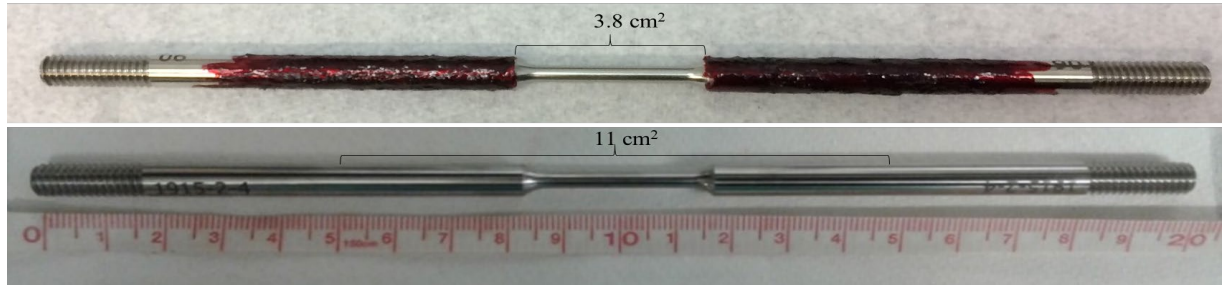






Material:
Carbon steel 1018 (UNS G10180)
and
API X65 steel

Solution:
NS4 soil solution

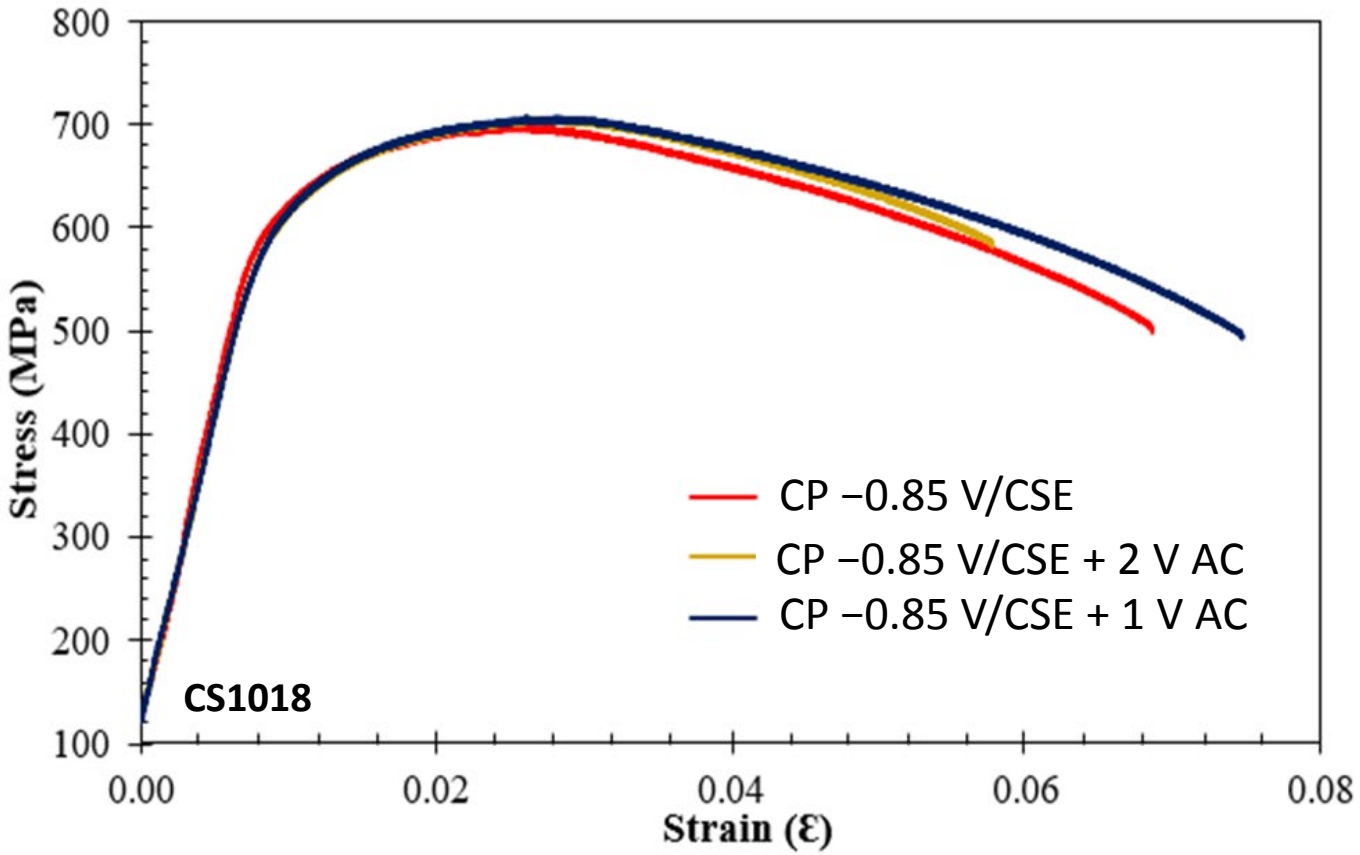


AC and DC (CP) Parameters

CP Potentials: −0.850, and −1.20 V/**CSE**
AC Voltages: 1, 2, 3 V (rms)
AC frequency: 60 Hz

STANDARDS: ASTM G-129 & NACE TM-198

RESULTS: STRESS-STRAIN CURVES

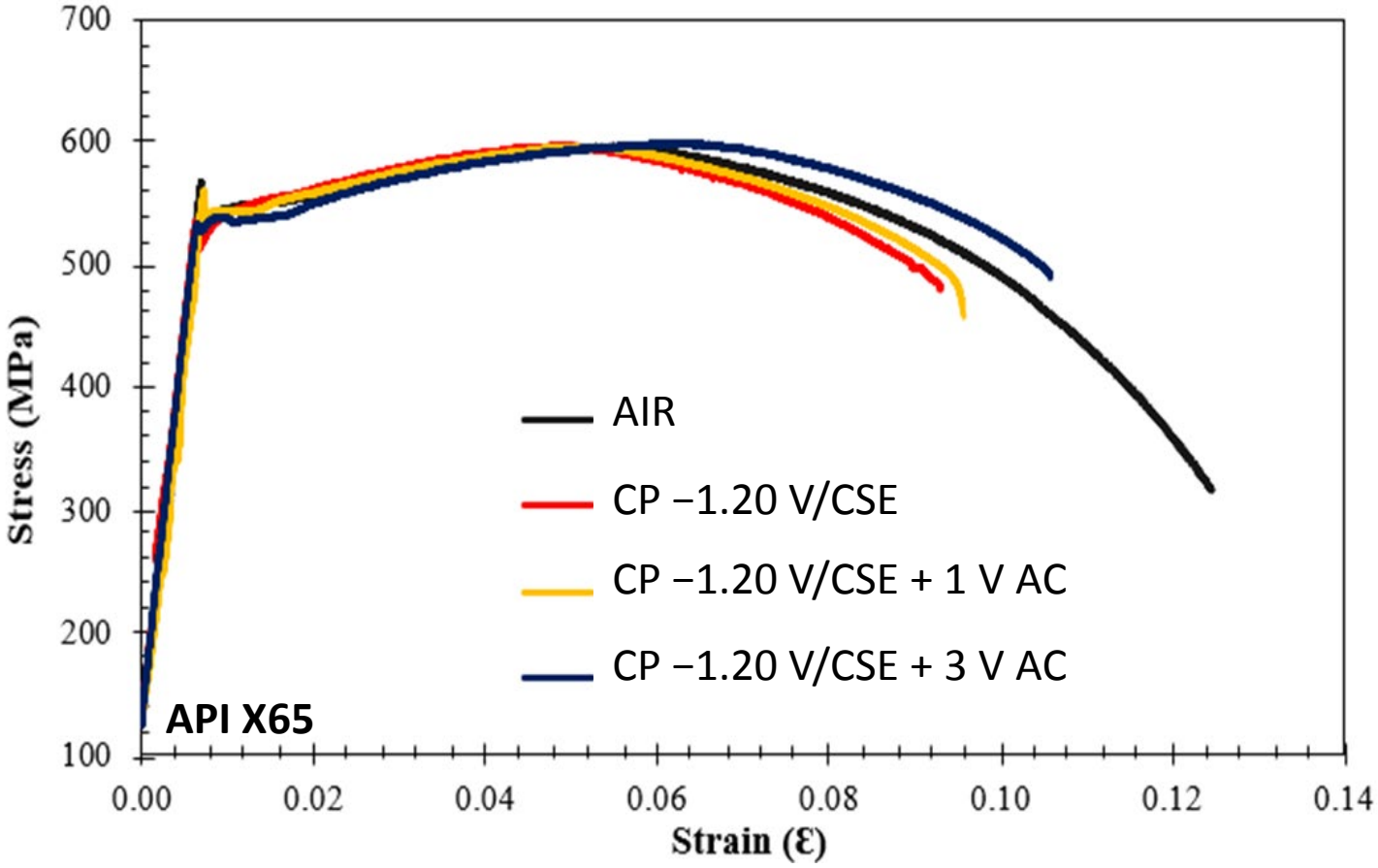


Environment* and Potentials	YS (MPa)	UTS (MPa)	Elongation (mm)
Air	651	716.4	2.35
CP	628	696.7	1.85
CP +1 V AC	640	707.4	2.02
CP +2 V AC	632	704.3	1.56

*In NS4 solution.

- ✓ Higher SCC susceptibility (more brittle behavior) at higher AC voltage.
- ✓ Higher elongation and less SCC damage were found at 1 V AC compared to that with CP only.

RESULTS: STRESS-STRAIN CURVES



Environment* and Potentials	YS (MPa)	UTS (MPa)	Elongation (mm)
Air	533	594.9	3.45
CP	512	596.0	2.41
CP +1 V AC	538	595.1	2.47
CP +3 V AC	527	598.1	2.74

*In NS4 solution.

- ✓ Higher elongation for API X65 than CS1018 in air.
- ✓ Ductility was significantly reduced under CP of −1.20 V/CSE.
- ✓ The 1 V AC curve showed a similar stress-strain curve to the one with CP potential only.
- ✓ 3 V AC had a slightly beneficial effect compared to that with CP potential only.

RESULTS: OPTICAL MICROSCOPY

CP −0.85 V/CSE **CP −1.20 V/CSE**

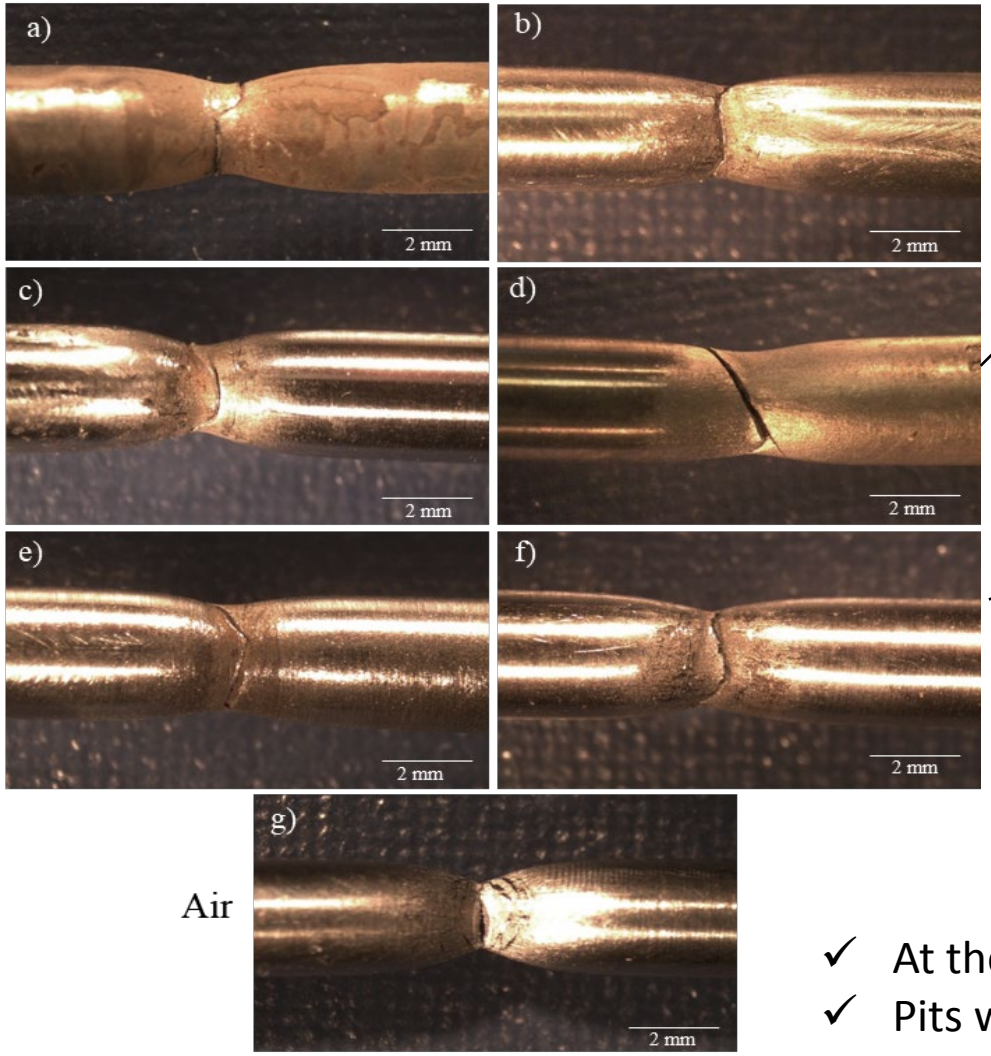
CS1018 API X65

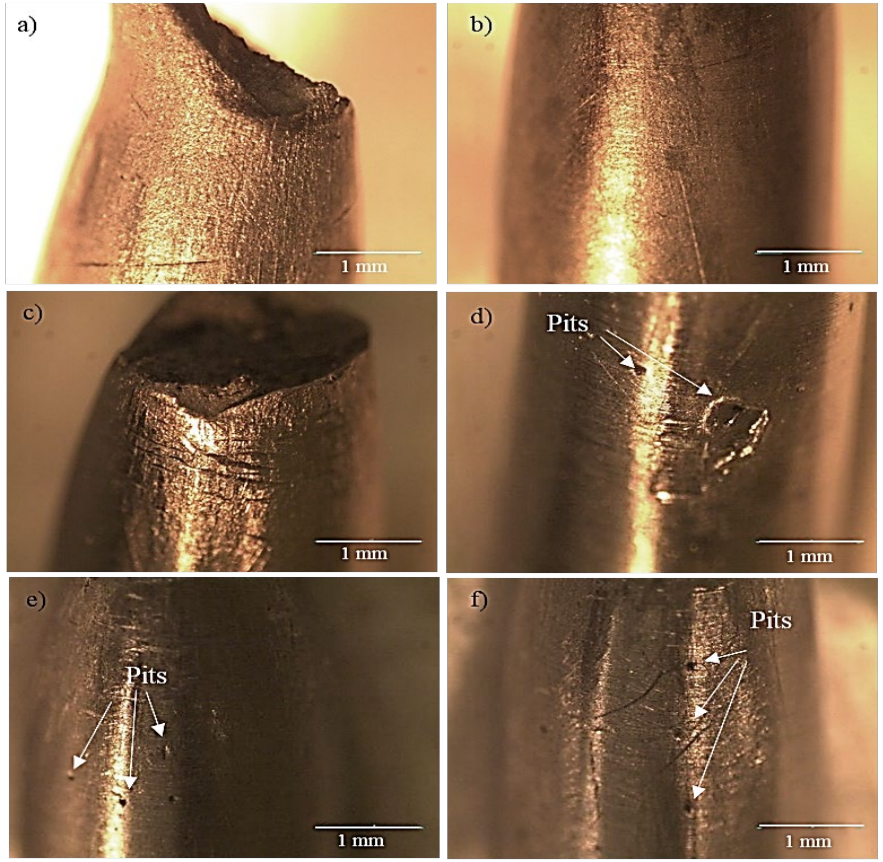
CP only

CP+1VAC

CP+high AC

Air





1 V AC

3 V AC

- ✓ At the same AC voltage (1 V), less area reduction d at more negative CP.
- ✓ Pits were found on the gauge section, at 3V AC and CP of −1.20 V/CSE.

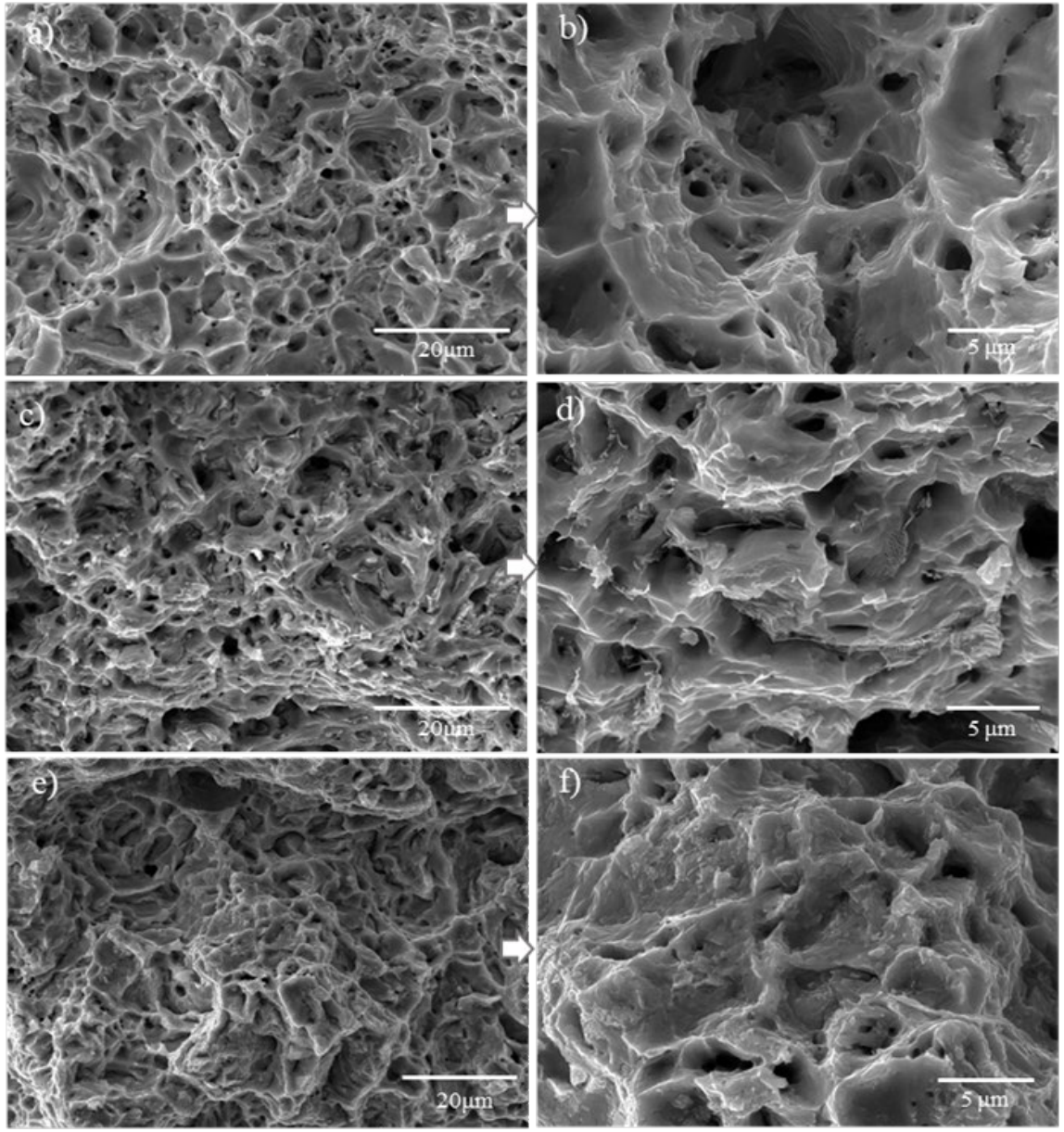
RESULTS: SEM MICROSCOPY

CP –0.85 V/CSE

CP ONLY

CP + 1 V AC

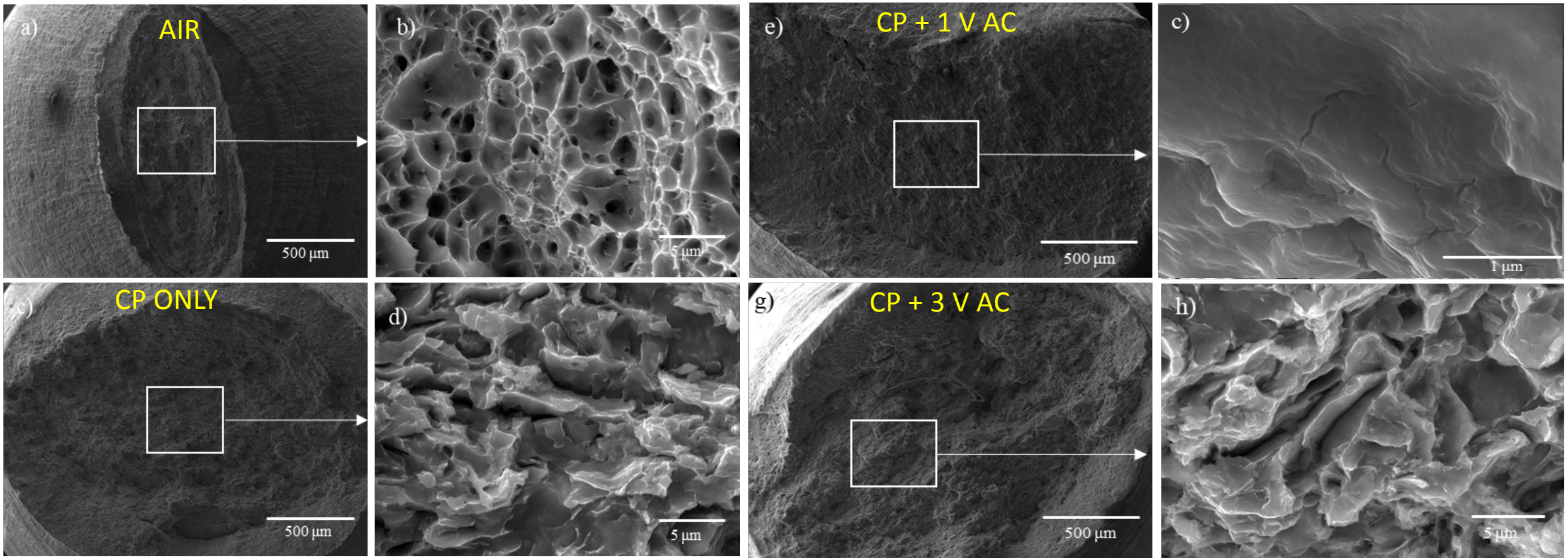
CP + 2 V AC



- ✓ The fracture morphology showed more brittle behavior at higher AC voltage with the appearance of quasi-cleavage zones.

RESULTS: SEM MICROSCOPY

CP −1.20 V/CSE



- ✓ Under CP only (without AC), the dimples (in air) disappeared and the morphology changed to mainly cleavage planes.
- ✓ The effect of AC on SCC is evidenced by the cracking found inside the fracture surface at 1 V AC with CP of −1.20 V/CSE.

RESULTS: SCC PARAMETERS

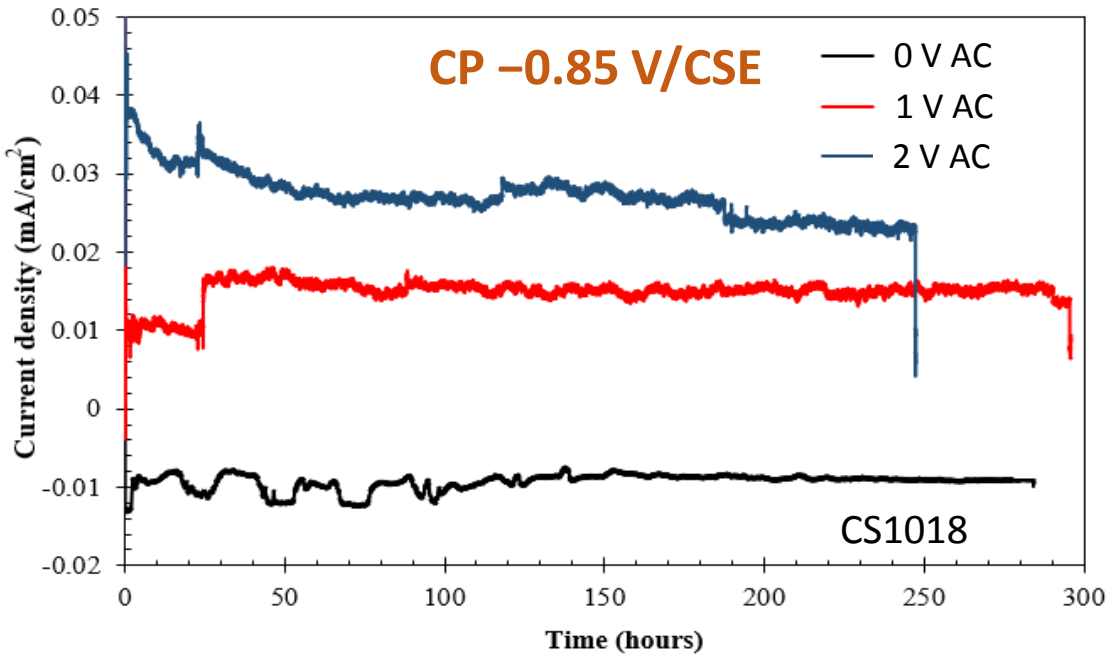
According to the NACE TM-198 and ASTM G129 standards

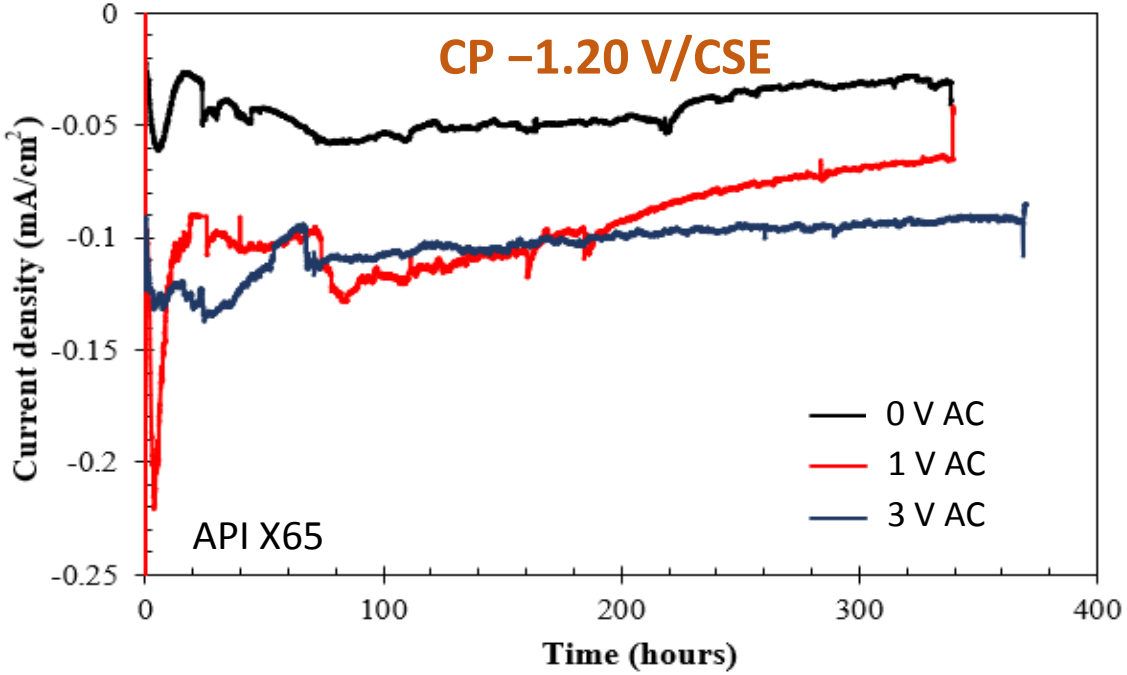
Material	Environment and Potentials*	**RTTF**	$I_\delta(\%)$	(%)RA	**RAR**
Carbon steel 1018	Air	-	-	52.60	-
	−0.85 V/CSE	0.94	19.11	47.95	0.91
	−0.85 V/CSE +1 V AC	0.98	15.96	39.94	0.76
	−0.85 V/CSE +2 V AC	0.81	29.13	34.39	0.65
Carbon steel API X65	Air	-	-	73.02	-
	−1.20 V/CSE	0.79	29.50	41.79	0.57
	−1.20 V/CSE +1 V AC	0.80	29.94	40.99	0.56
	−1.20 V/CSE +3 V AC	0.86	26.37	39.01	0.53

*In NS4 solution.

- ✓ The plasticity loss, $I_\delta(\%)$, was greater with **2 V AC** under −0.85 V/CSE.
- ✓ For −1.20 V/CSE with different AC voltages, the plasticity loss did not show a noticeable difference.
- ✓ The high susceptibility to EAC (RTTF and RAR) was found **at CP of −1.20 V/CSE, without AC**.

RESULTS: CURRENT DENSITY UNDER CP AND AC CONDITIONS





- ✓ A *positive* shift in the current density was observed when the AC voltage was applied.
- ✓ The current density magnitude increased as the AC voltage increased from 1 V to 2 V.

- ✓ Higher *negative* current densities were found with applied AC voltages.
- ✓ No clear difference between 1 and 3 V AC.

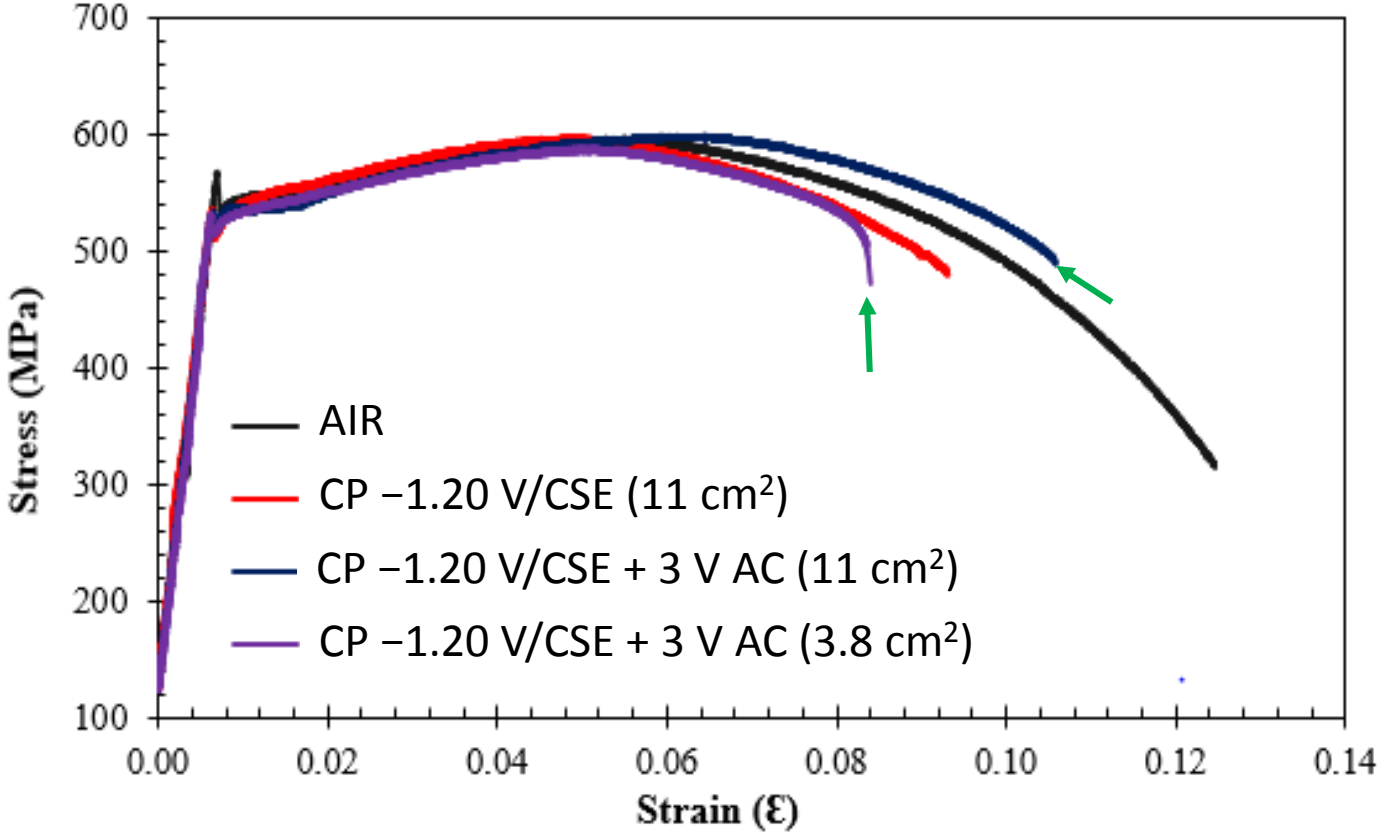
DC currents depends on CP!

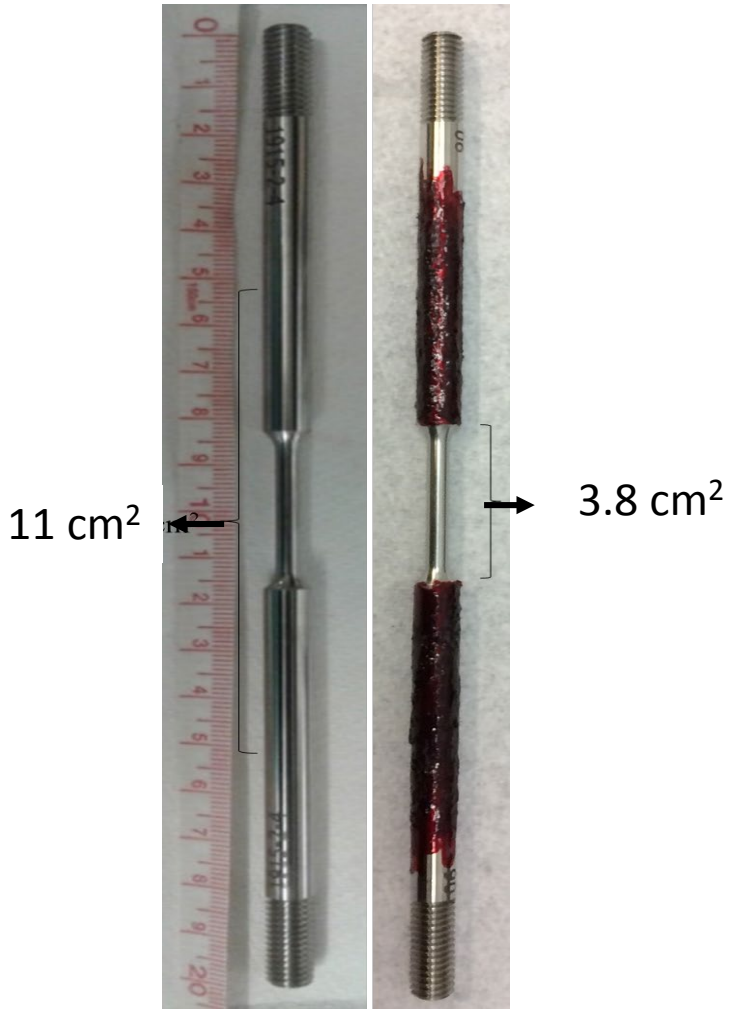
CP (V/CSE)	AC VOLTAGES APPLIED (V rms)	AC CURRENT DENSITIES (A/m²)
−0.850	1	22-14
	2	34-25
−1.20	1	23-11
	3	61-35

- ✓ Higher AC current densities at higher AC voltages.

RESULTS: STRESS-STRAIN CURVES WITH ENHANCED AC CURRENT DENSITY

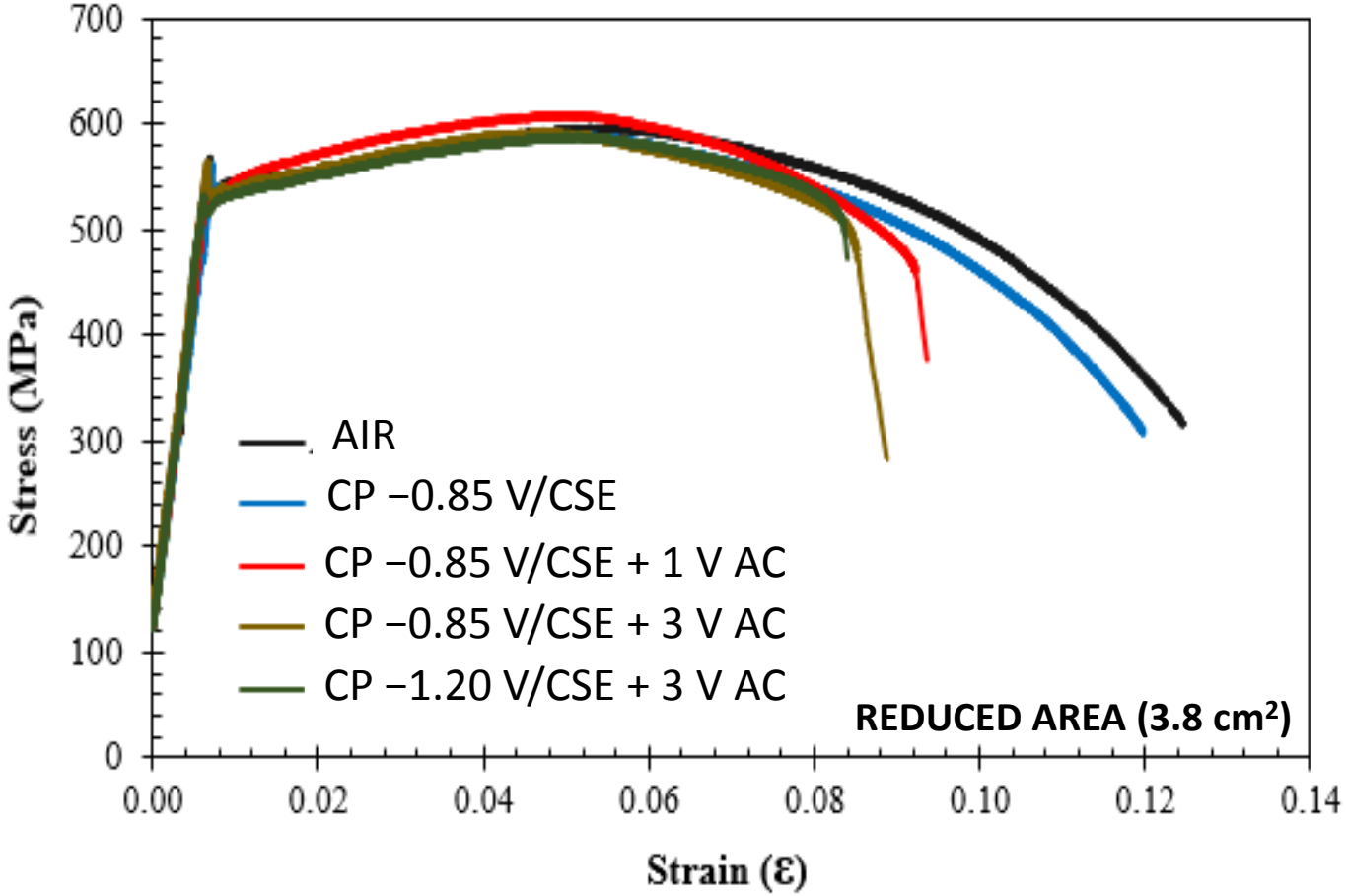
- The exposed area was reduced to (1) **increase AC current density**, and (2) evaluate its effect on **pitting severity**.





- ✓ The sample with reduced area (3.8 cm²) showed a greater loss of ductility, and lower yield stress compared to the sample with larger exposed area (11 cm²).
- ✓ An Increase in the SCC susceptibility was observed when the exposed area was reduced (AC current density increased around 30 A/m²).

RESULTS: STRESS-STRAIN CURVES WITH ENHANCED AC CURRENT DENSITY



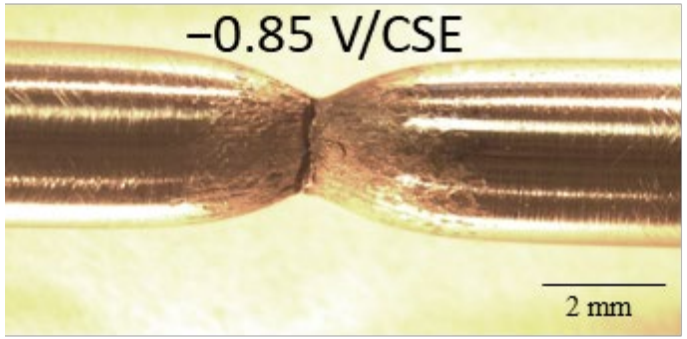
Environment and CP/AC potentials	YS (MPa)	UTS (MPa)	Elongation (mm)
Air	533	594.9	3.45
−1.20 V/CSE + 3 V AC	515	587.5	2.32
−0.85 V/CSE	536	588.3	3.14
−0.85 V/CSE + 1 V AC	519	607.0	2.50
−0.85 V/CSE + 3 V AC	530	590.7	2.40

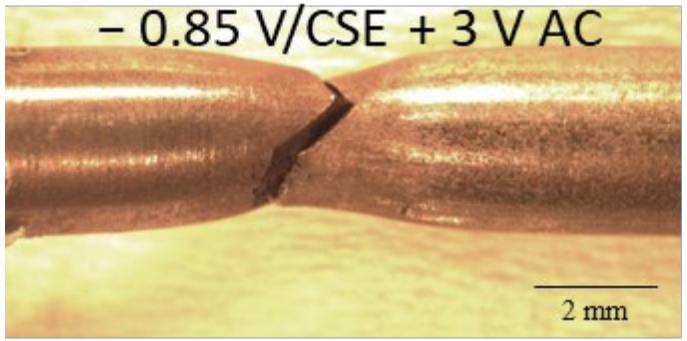
*In NS4 solution, 3.8 cm^2 area.

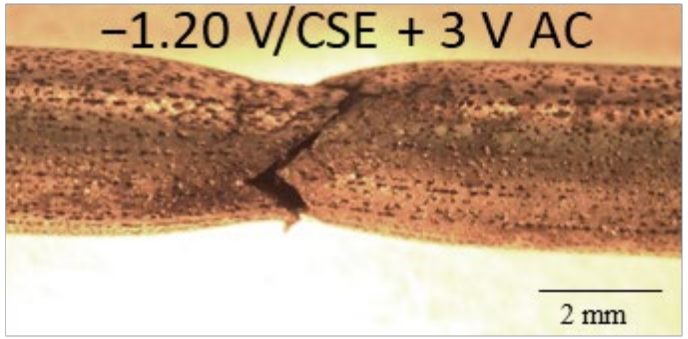
For −0.85 V/CSE + 1 V AC , the AC current density increased around 18 A/m^2

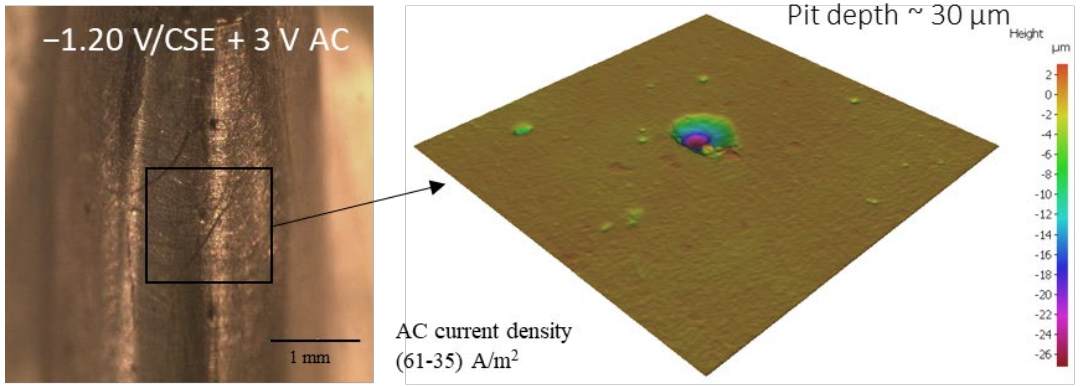
- ✓ Reduction in ductility and deterioration of mechanical properties (YS) were obtained with increasing AC voltages.
- ✓ The curves under 3 V AC with different CP showed similar behavior.

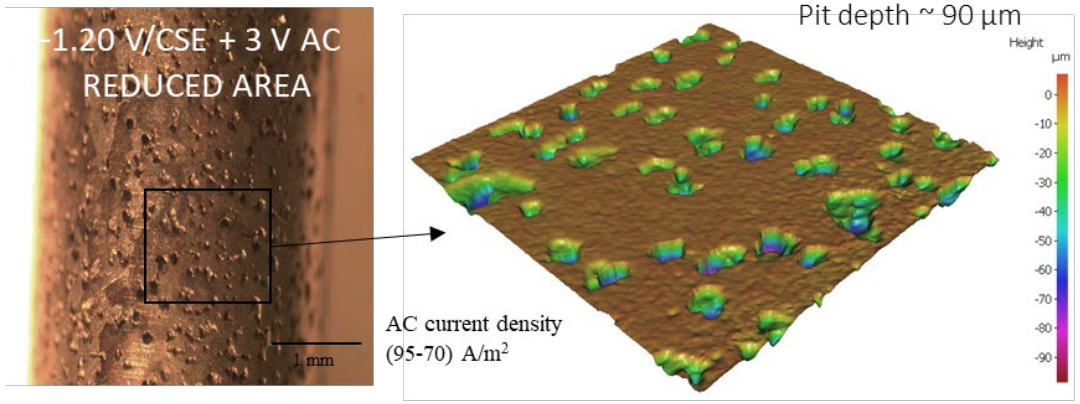
RESULTS: OPTICAL MICROSCOPY

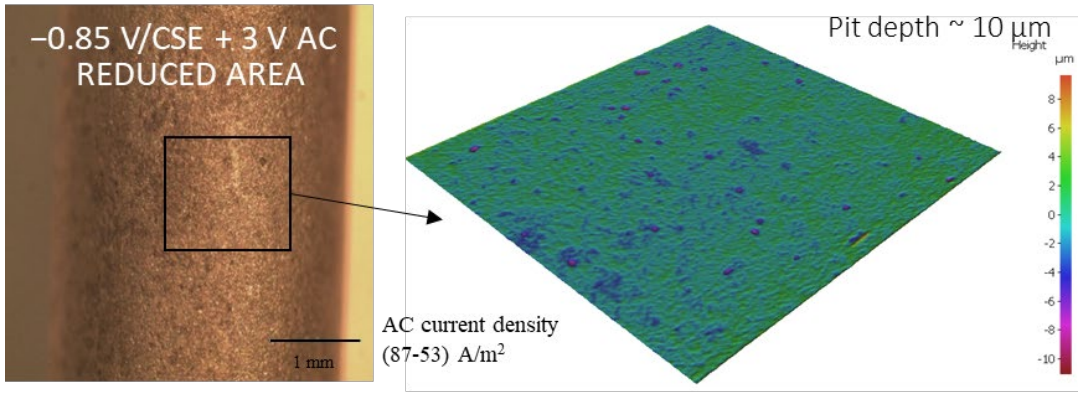












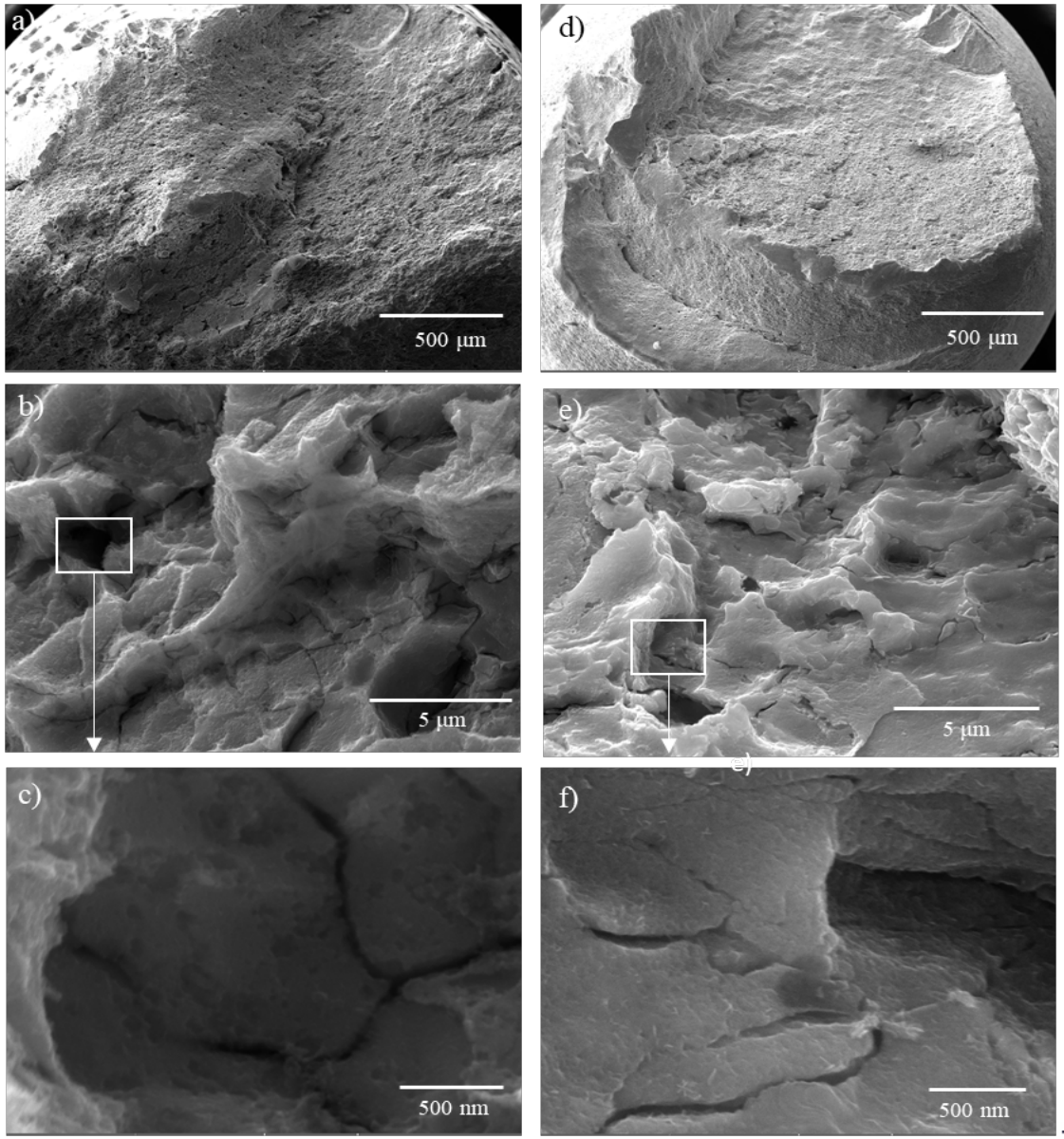
- ✓ The necking formation was more pronounced for the sample with CP only.
- ✓ Higher AC current density increased the intensity of pitting corrosion.
- ✓ Under 3 V AC with reduced area, the pitting severity (e.g., depth) was higher at lower CP potential.

RESULTS: SEM MICROSCOPY

3 V AC

with reduced surface area of 3.8 cm²

−1.20 V/CSE | **−0.85 V/CSE**



- ✓ Predominantly brittle fracture regions with quasi-cleavage planes for both samples.
- ✓ The cathodic potential did not noticeably change the cracking morphology.

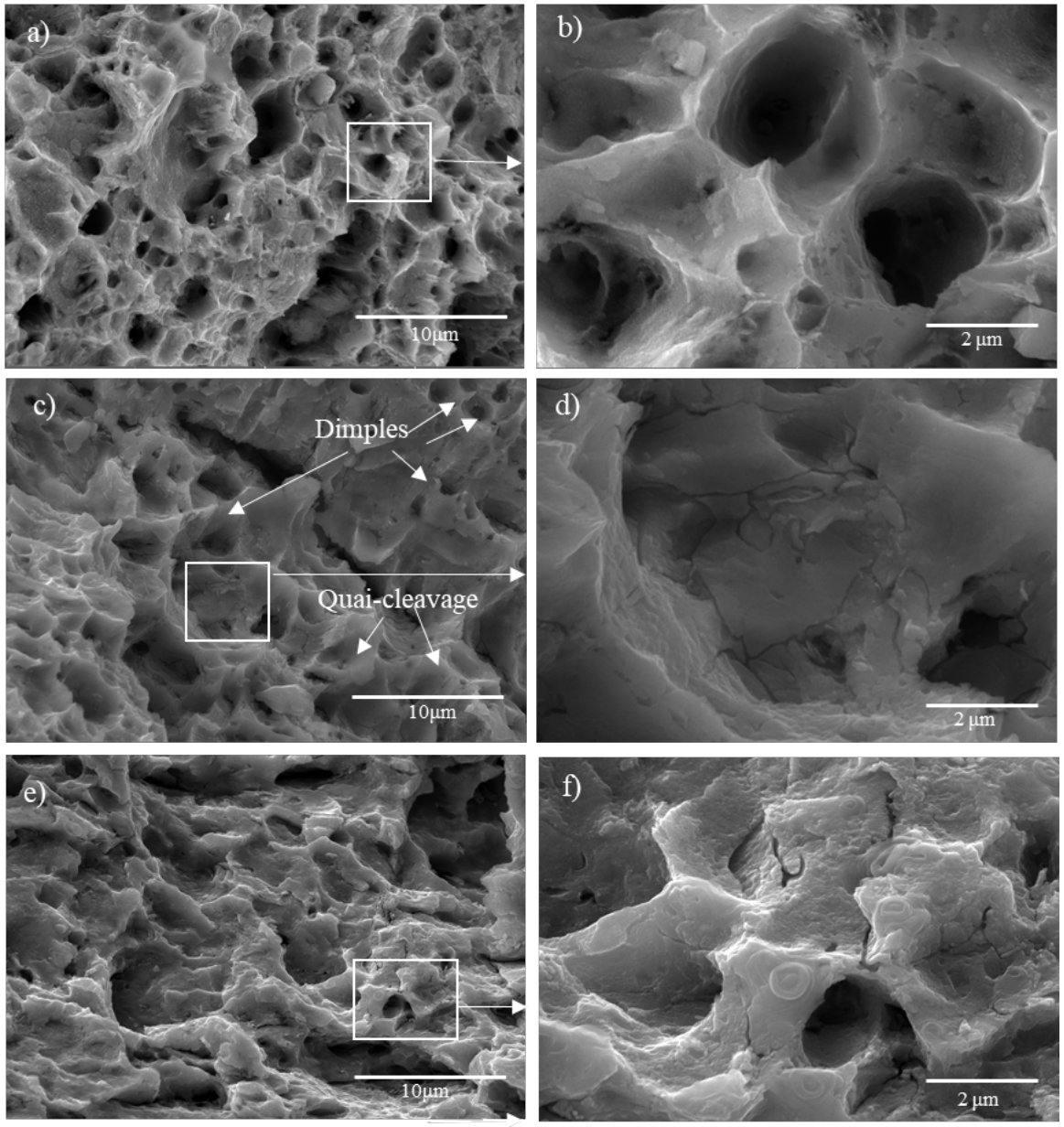
RESULTS: SEM MICROSCOPY

–0.85 V/CSE only

–0.85 V/CSE + 1 V AC

–0.85 V/CSE + 3 V AC

with reduced surface area of 3.8 cm²

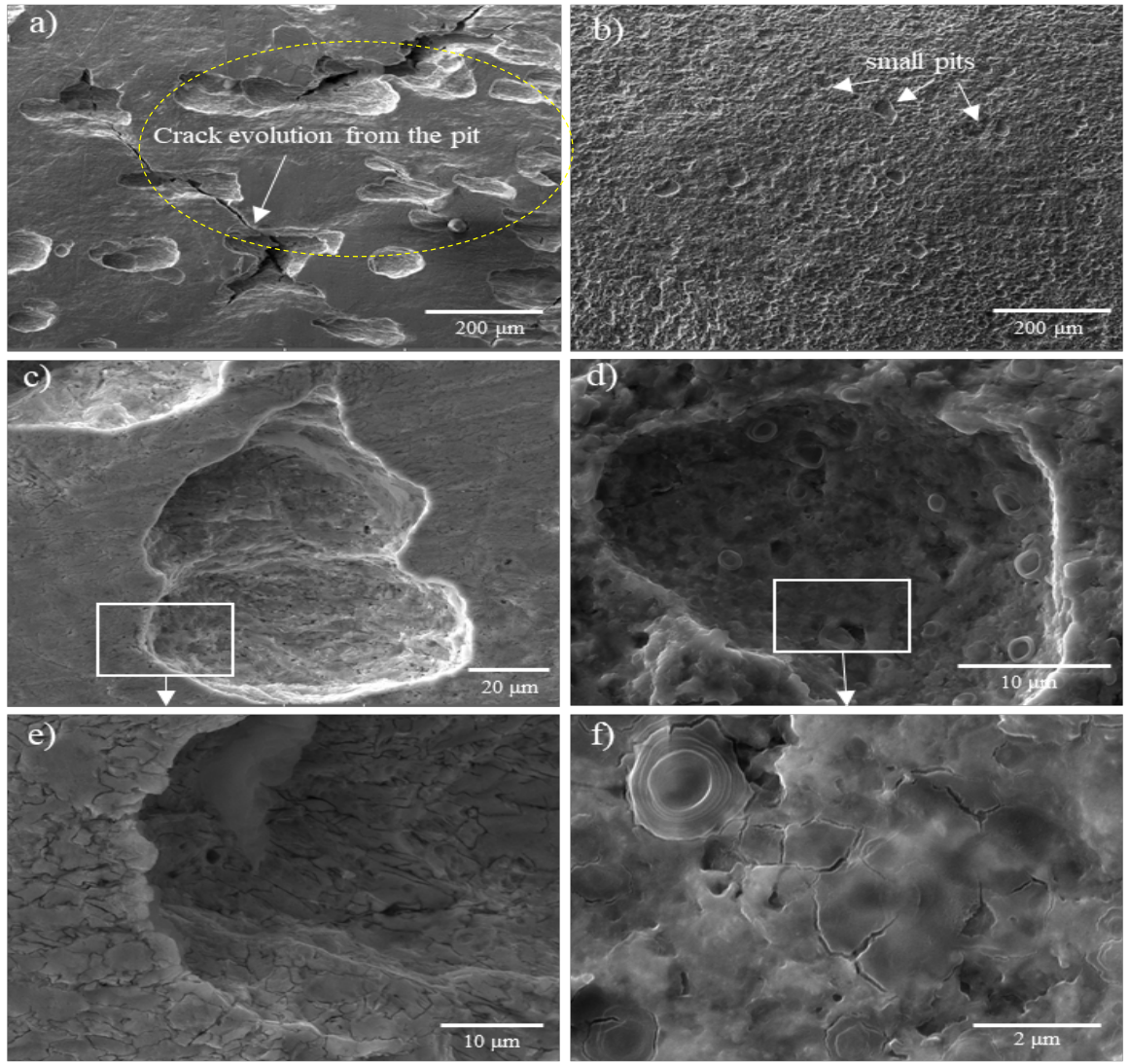


- ✓ The relative ratio of the dimples to quasi-cleavage planes decreased with increasing AC voltage.
- ✓ Brittle morphology is observed at the highest AC voltage.

RESULTS: SEM MICROSCOPY

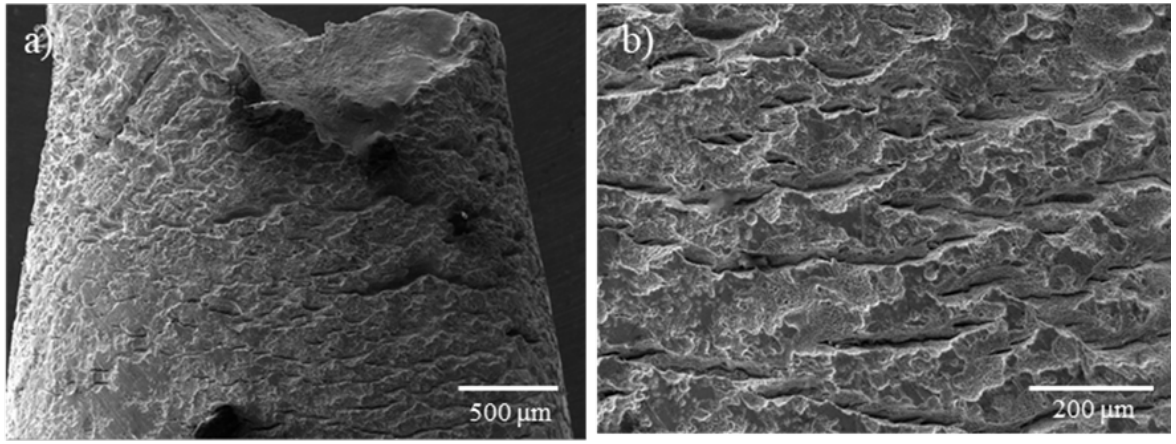
−1.20 V/CSE + 3 V AC

−0.85 V/CSE + 3 V AC



Gauge section (necking region)

−1.20 V/CSE + 1 V AC



- ✓ Pitting corrosion became more severe with larger pit depth at lower cathodic potential (−1.20 V/CSE).
- ✓ Secondary cracking morphology suggests SCC susceptibility under AC.

RESULTS: SCC PARAMETERS

According to the NACE TM-198 and ASTM G129 standards

With enhanced AC current density (smaller area)

SCC susceptible (RTTF/RAR low)

Environment	CP potential (V/CSE)	AC potential (V rms)	**RTTF**	I_δ (%)	(%)RA	**RAR**
Air	-	-	-	-	73	-
NS4		0	0.96	8.89	71	0.98
	−0.85	1	0.78	26.37	44	0.62
		3	0.73	30.40	37	0.51
	−1.20	**3**	0.72	32.50	29	0.40

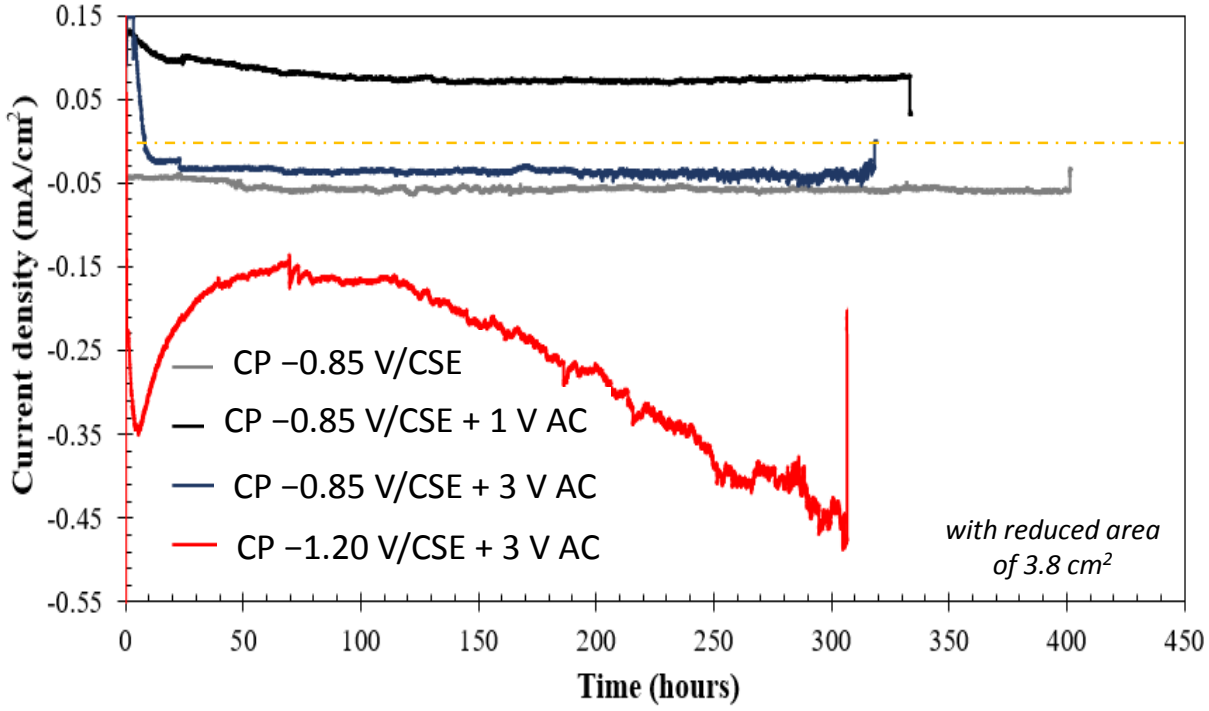
Comparison (with larger area)

Environment and Potentials*	**RTTF**	I_δ(%)	(%)RA	**RAR**
−0.85 V/CSE +1 V AC	0.98	15.96	39.94	0.76
−1.20 V/CSE +3 V AC	0.86	26.37	39.01	0.53

✓ SCC susceptibility increased with increasing applied AC voltage and AC current density.

RESULTS: CURRENT DENSITY WITH REDUCED AREA

CURRENT DENSITY vs. TIME



AC CURRENT DENSITIES MEASURED

CP POTENTIAL (V/CSE)	EXPOSED AREA (cm^2)	AC VOLTAGE APPLIED (V rms)	AC CURRENT DENSITIES (A/m^2)
−0.85	11	1	22 - 14
	11	2	34 - 25
	3.8	1	40 - 19
	3.8	3	87 - 53
−1.20	11	1	23 - 11
	11	3	61 - 35
	3.8	3	95 - 70

AC current densities associated with higher SCC susceptibility

- ✓ A positive shift in the current density was found when 1 V AC was applied at −0.85 V/CSE.
- ✓ The DC current density shifted to more cathodic values under the highest AC voltage and CP potential.

- ✓ Samples with reduced area showed higher AC current densities, therefore higher SCC susceptibility.

CONCLUSIONS AC-SCC

The AC interference imposed on carbon steels affected the SCC susceptibility in NS4 solution. Changes in the electrochemical activity of the steels under the AC interference were found to depend on the CP potentials applied.

- At CP of **−0.85 V/CSE**, higher susceptibility was found at higher AC voltage and current density.

- At CP of **−1.20 V/CSE**, the AC interference generated more negative currents that accelerated the cathodic reactions (e.g., HER) on the steel surface and promoted the SCC susceptibility. The SCC susceptibility increased with an increase in the AC current densities. For the AC voltage of 3 V, the enhanced AC current increased the cracking susceptibility.

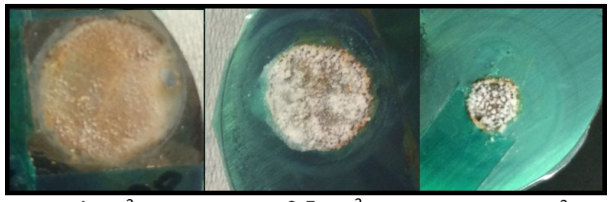
- The fracture morphology showed a transition from ductile to brittle fracture with more negative cathodic potential and higher AC current density. The maximum susceptibility was found at 3 V AC with an AC current density of ~90 A/m^2. Pitting and secondary cracks were found in the gauge sections of the SSR specimens. Higher pitting severity occurred at higher AC current densities. Pitting to cracking transition is hypothesized to be responsible.

PITTING STUDY

A pitting study was performed to understand the influence of AC current density on pitting severity.

CP –1.20 V/CSE

Areas of immersion



1 cm² 0.5 cm² 0.16 cm²

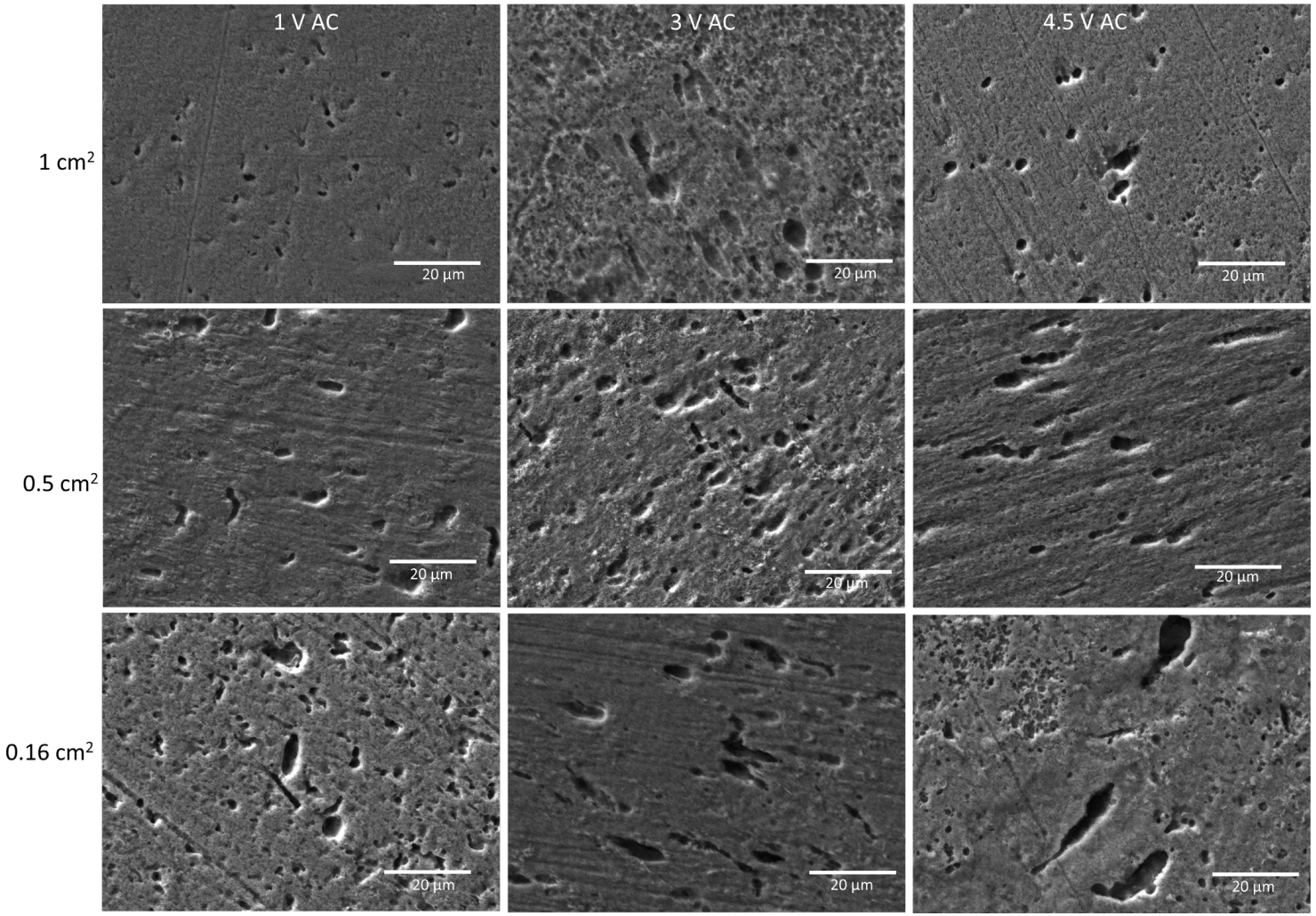
AC Voltages: 1, 3, 4.5 V (rms)

Average AC current density (A/m²)			
Area	1 V AC	3 V AC	4.5 V AC
1 cm²	30.40	85.20	107.86
0.5 cm²	39.44	138.30	181.52
0.16 cm²	44.80	190.00	312.20

Maximum pitted area (µm²)			
Area	1 V AC	3 V AC	4.5 V AC
1 cm²	12	25	32
0.5 cm²	30	24	50
0.16 cm²	55	50	120

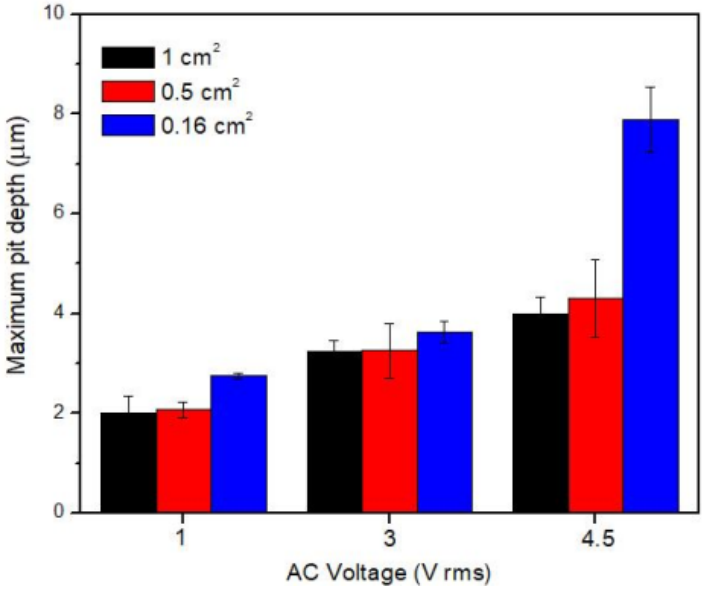
Pit Area ⬆ when ⬆ AC current ⬇ Exposed area

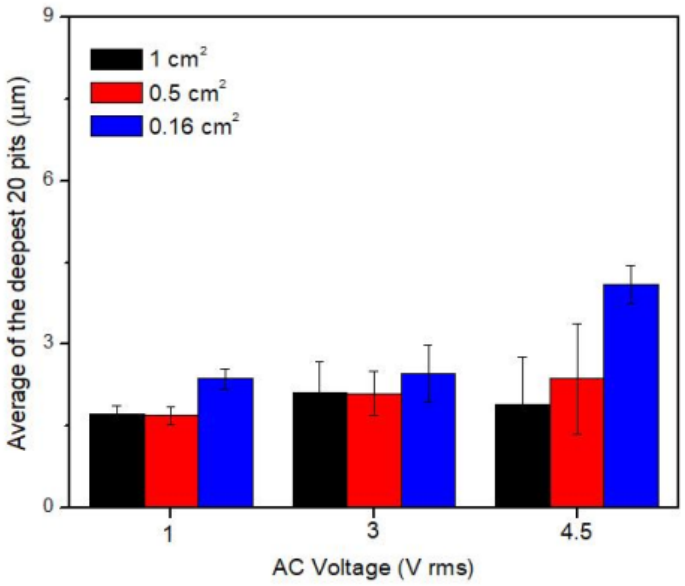
SEM RESULTS



PITTING STUDY

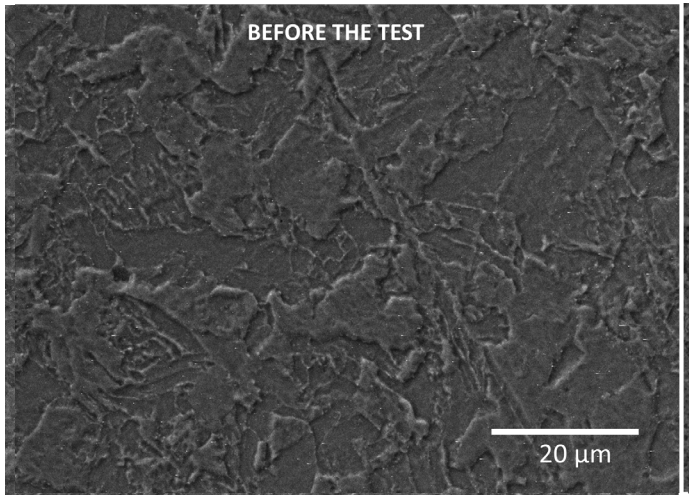
CP –1.20 V/CSE

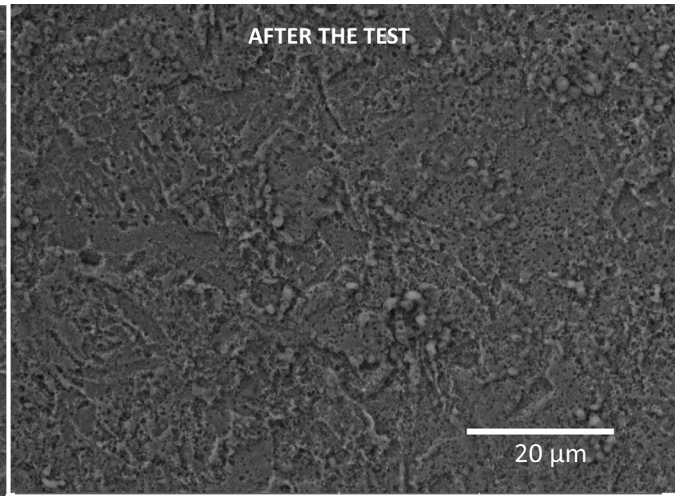




Pit depth ⬆ when ⬆ AC current ⬇ Exposed area

The API X65 microstructure is composed of mainly M/A islands with different shapes inside a ferrite matrix (α-Fe).





Preferential pitting initiation in the M/A (Martensite-Austenite) islands

SELECTED REFERENCES

1. NACE International Task Group 327, “AC Corrosion State-of-the-Art: Corrosion Rate, Mechanism, and Mitigation Requirements” January 2010.
2. M. Yunovich, N.G. Thompson, “AC Corrosion: Mechanism and Proposed Model”, International Pipeline Conference (IPC) ASME International, 2004), p. IPC04.
3. R.A. GUMMOW, P.ENG, NACE CORROSION SPECIALIST NO.17. AC Interference guideline final report. CORRENG CONSULTING SERVICE INC. Canada, 2004.
4. A. Brenna, M.V. Diamanti, L. Lazzari, M. Ormellese. A proposal of AC mechanism in cathodic protection. NSTI-Nanotech 2011. ISBN 978-1-4398-7138-6. Vol.3. 553-556.
5. Xu, L.Y., X. Su, and Y.F. Cheng, Corros. Sci. 66 (2013): pp. 263–268.
6. M. Büchler, C. H. Voute, F.S., “Characteristics of Potential Measurements In the Field of AC Corrosion Zusammenfassung Résumé,” in Ceocorr (2013), pp. 1–10.
7. Zhu, M., Du, C., Li, X., Liu, Z., Li, H., & Zhang, D. (2014). Effect of AC on stress corrosion cracking behavior and mechanism of X80 pipeline steel in carbonate / bicarbonate solution. Corrosion Science, 87, 224–232.
8. Wan, H., Song, D., Liu, Z., Du, C., Zeng, Z., Yang, X., & Li, X. (2017). Effect of alternating current on stress corrosion cracking behavior and mechanism of X80 pipeline steel in near-neutral solution. Journal of Natural Gas Science and Engineering, 38, 458–465.
9. Jones, R. H., & Ricker, R. E. (1992). Mechanisms of Stress-Corrosion Cracking. In Stress-Corrosion Cracking Materials Performance and Evaluation (pp. 1–10).
10. T. Zhang, W.Y. Chu, K.W. Gao, L.J. Qiao. Study of correlation between hydrogen-induced stress and hydrogen embrittlement. Materials Science and Engineering A347 (2003) 291/299.

ACKNOWLEDGEMENT

- This work is funded by USDOT/PHMSA under cooperative agreement DTPH5615HCAP02.
- Marathon Petroleum Company
- Mears Integrity Solutions