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The Effect of Cathodic Protection on NNSCC Crack Growth in a Simulated Buried Pipeline Disbondment: Paper No. 16

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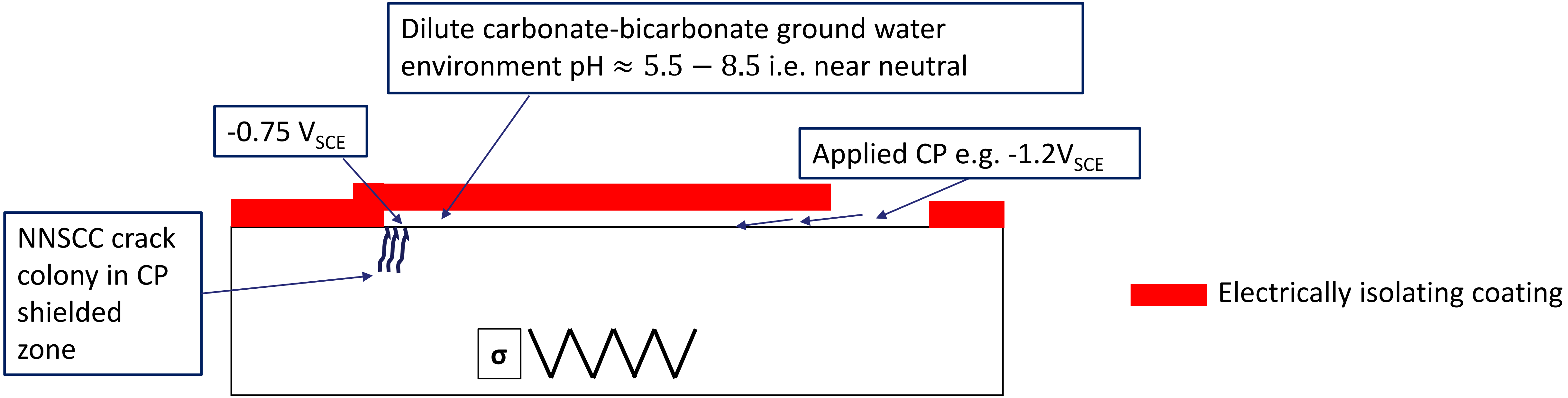
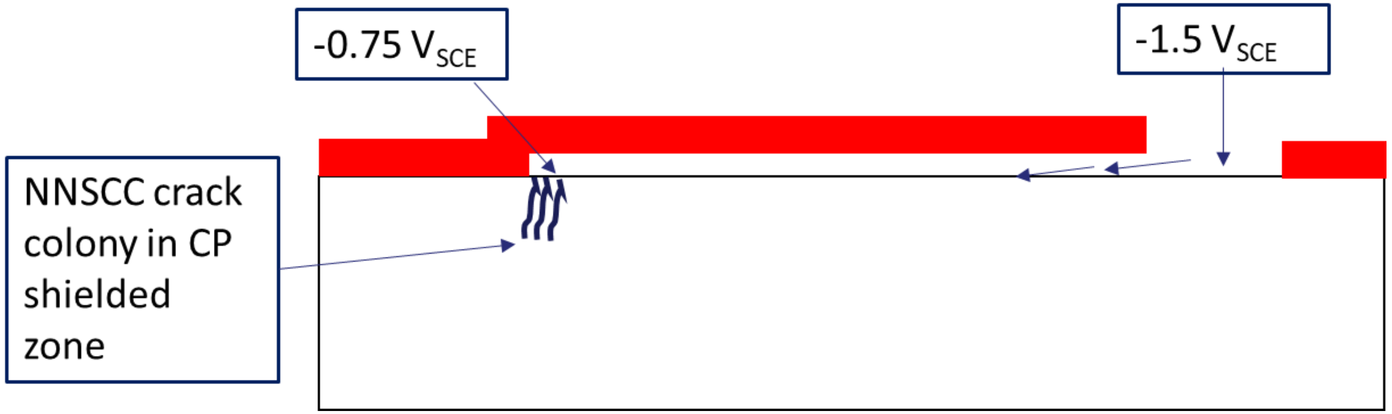
Introduction (1)

- Near neutral stress corrosion cracking in buried gas/oil pipelines:



- Pipeline operators encountering NNSCC need to understand the role of CP on NNSCC crack growth… will increasing CP be worse???

Some Aims.....



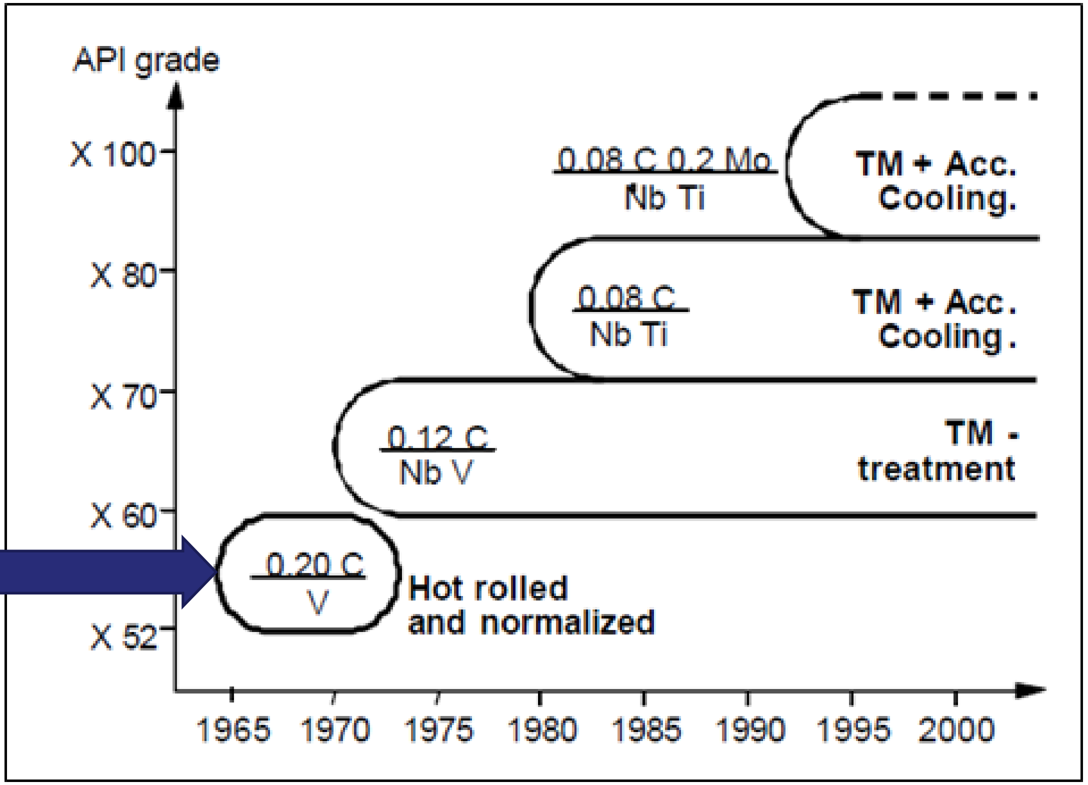
Motivation for EPRG project 204 To understand the effect of different CP levels on NNSCC crack propagation

- Simulate the field situation with a suitable small scale laboratory crack growth method.
- Determine the NNSCC crack growth rate for different applied potentials.
- Evaluate the role of CP and possible long range H diffusion on the (shielded) crack velocity.

Pipe material (1)

- API X60 grade pipe from early 1970s with 13.4 mm WT and OD of 914.4 mm.

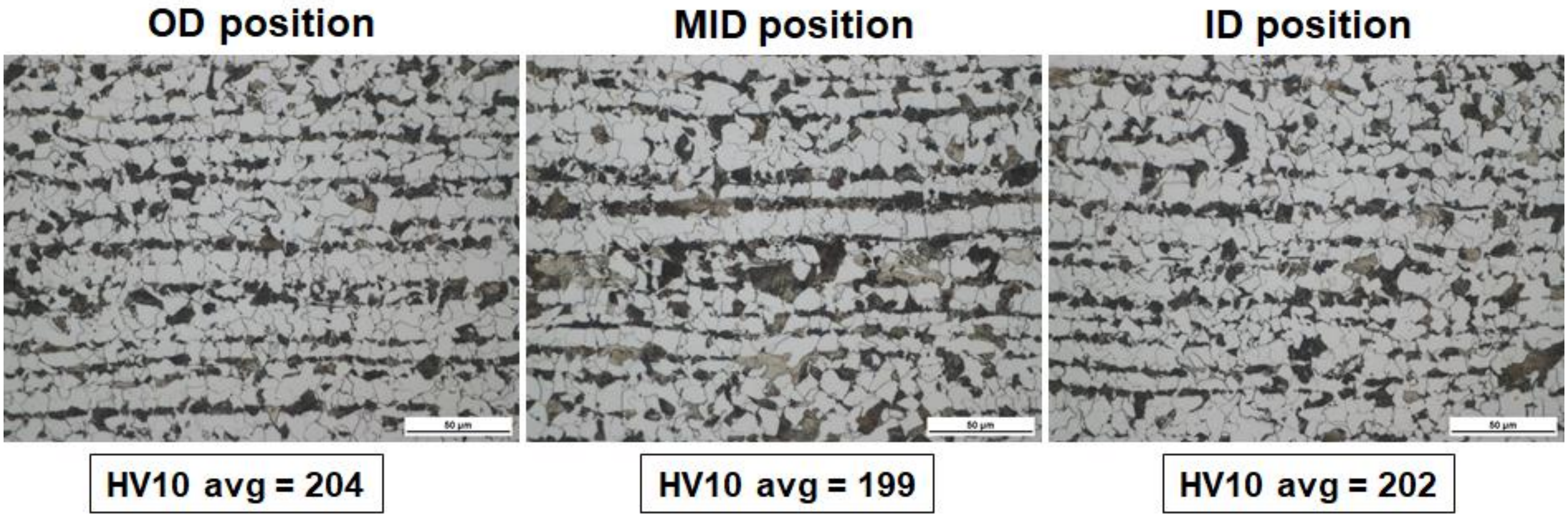
C	Mn	Si	Nb	V	Ti	P	S
0.19	1.40	0.38	0.029	0.071	<0.01	0.014	0.013



H. Hillenbrand, M. Graf, and C. Kalwa, Niobium Science & Technology. TMS (2001), p. 543-569.

Pipe material (2)

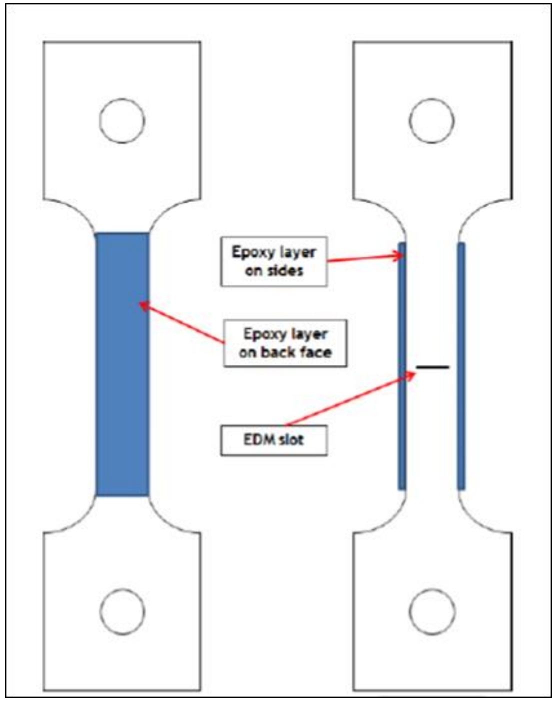
- Longitudinal mechanical properties: AYS = 444 MPa, UTS = 642 MPa.



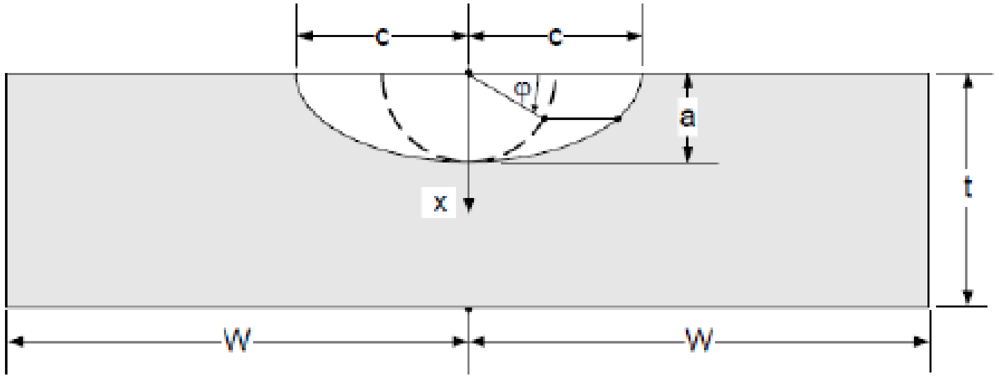
Experimental setup (Specimen design)

- The experimental approach was inspired by earlier Canadian published works (Uni Alberta-TransCanada-Spectra Energy).

- Flat tensile specimens machined to simulate a pre-existing shallow NNSSC surface crack:



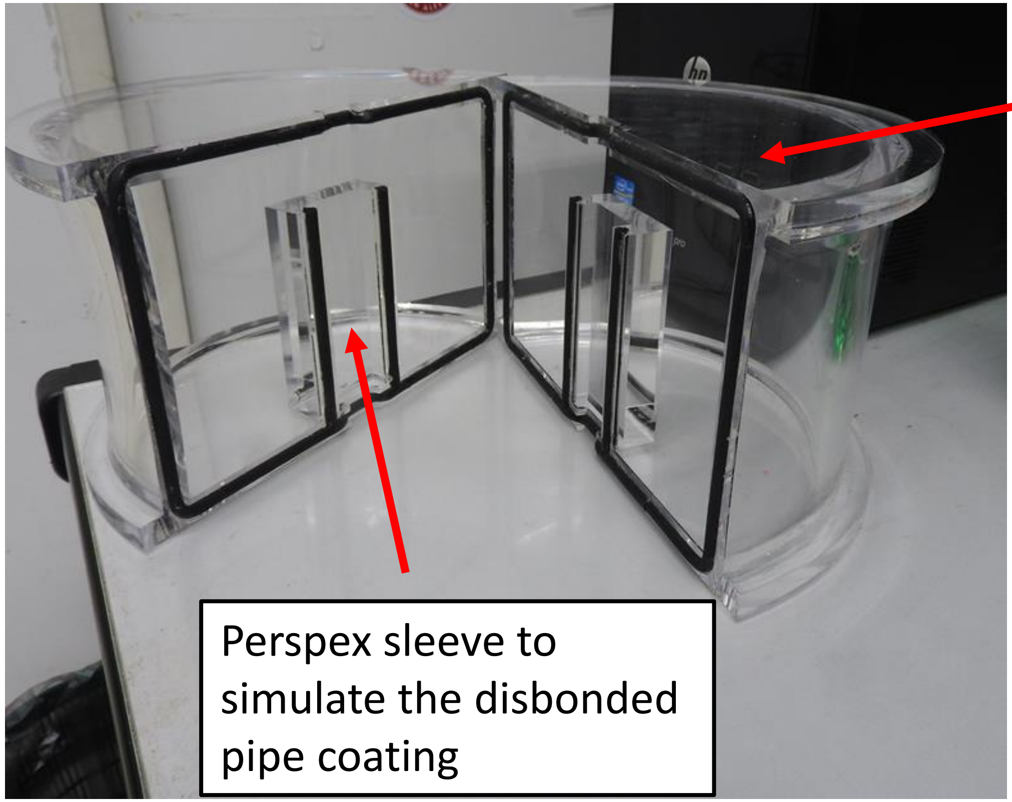
Epoxy coated so that only one face with notch exposed – to simulate pipe OD.



a = 2.5 mm. 2c = 5 mm

Experimental setup (Environment and Disbondment)

- Test cell manufactured to simulate a disbondment of 5 mm



Perspex outer chamber

Test solution fed into cell – synthetic soil solution known as “C2”

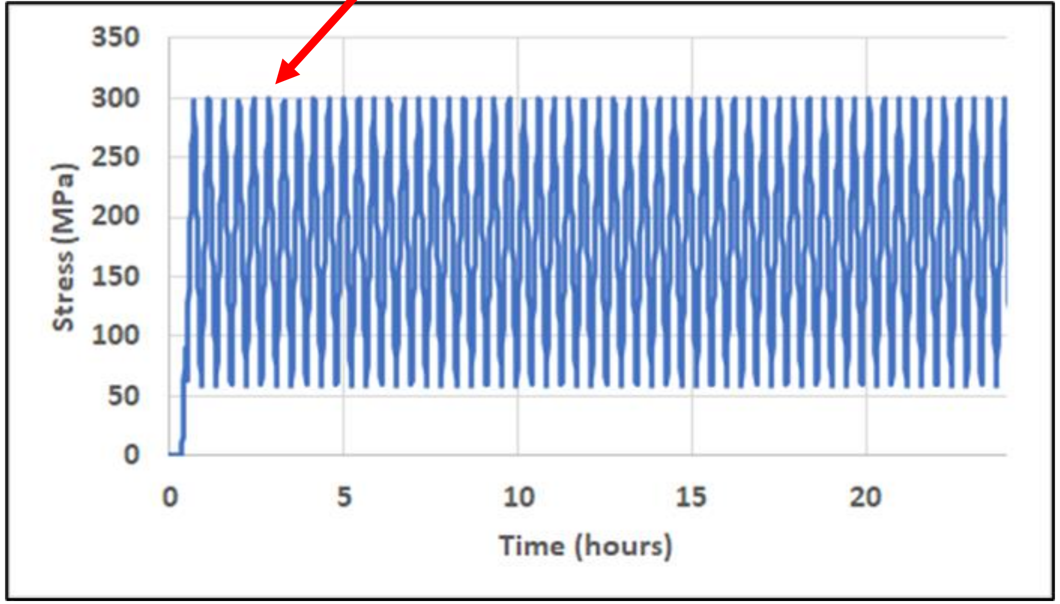
Solution	KCl (g/l)	$NaHCO_3$ (g/l)	$CaCl_2.H_2O$ (g/l)	$MgSO_4.7H_2O$ (g/l)	$CaCO_3$ (g/l)	Conductivity (S/m)
C2	0.0035	0.0195	0.0255	0.0274	0.0606	0.0075

Test gas bubbled through solution during test: 5% CO2/N2

Experimental setup (Mechanical loading)

- A slow strain rate machine was adapted to perform cyclic loading on the precracked samples.

Fatigue loading performed to simulate pipeline pressure fluctuations



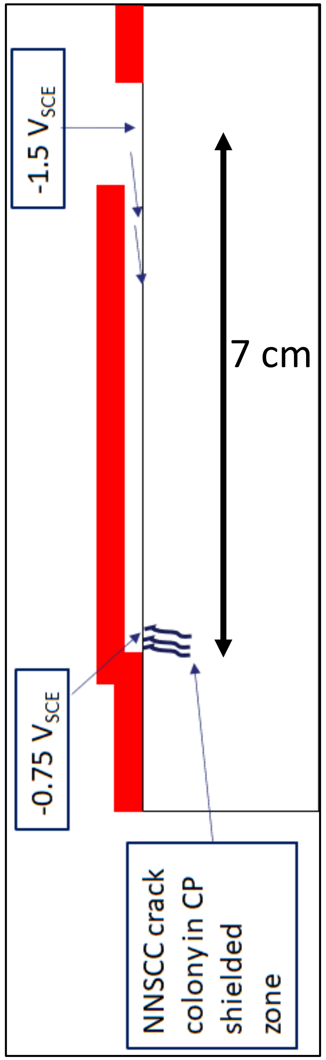
Max load was 72% of SMYS = 0.72 X 415 MPa

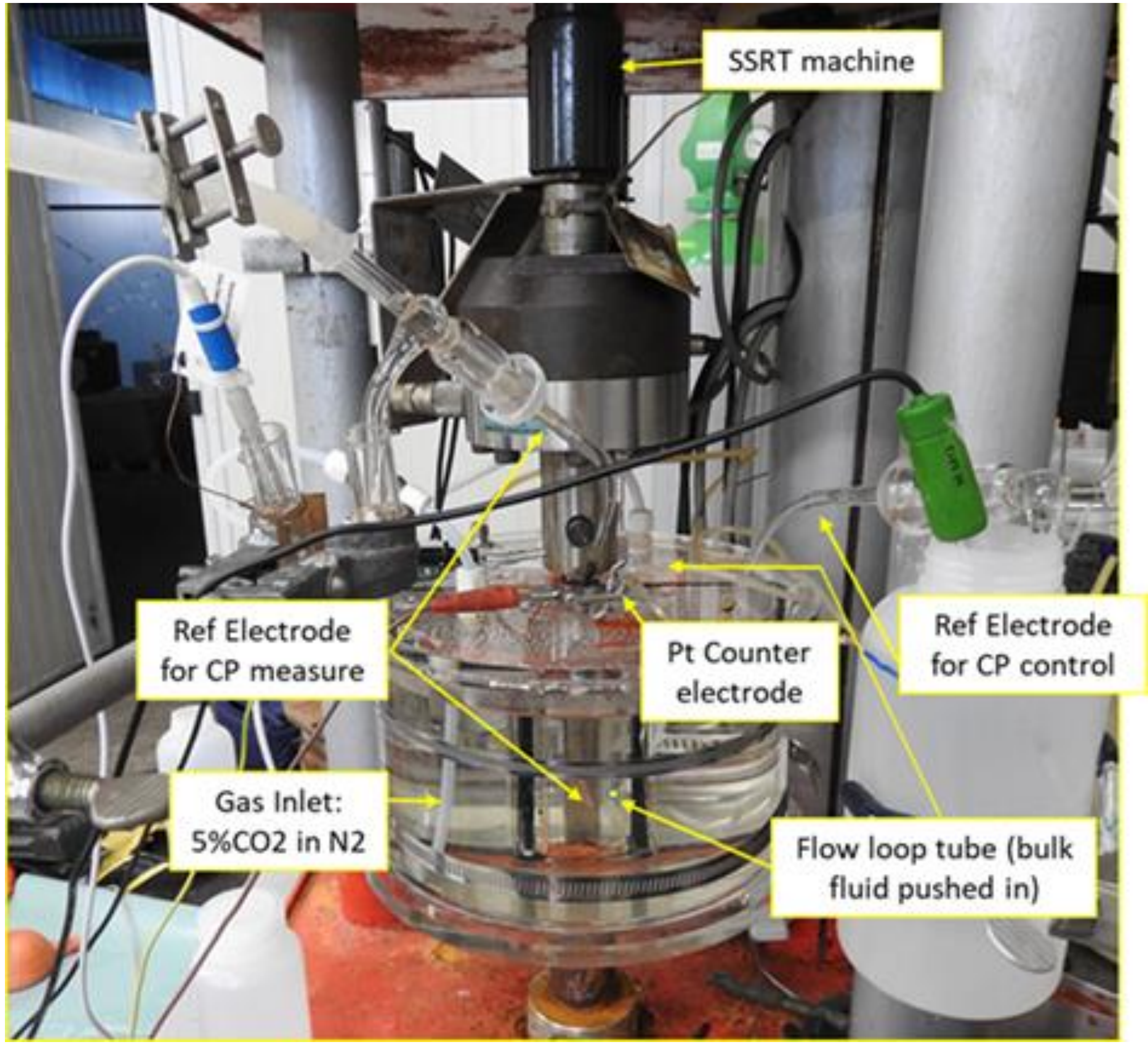
R value set to 0.2 after trials showed no crack growth at R = 0.6 or 0.9

Frequency was set to 6.4 X 10^{-4} Hz (about 1.5 X 10^{-6} /s)

Around two cycles per hour were achieved with these parameters

Experimental setup (Putting it all together….)





Test duration max 35 days (max 1900 cycles)

CP potential applied at "open mouth" – at top of Perspex sleeve.

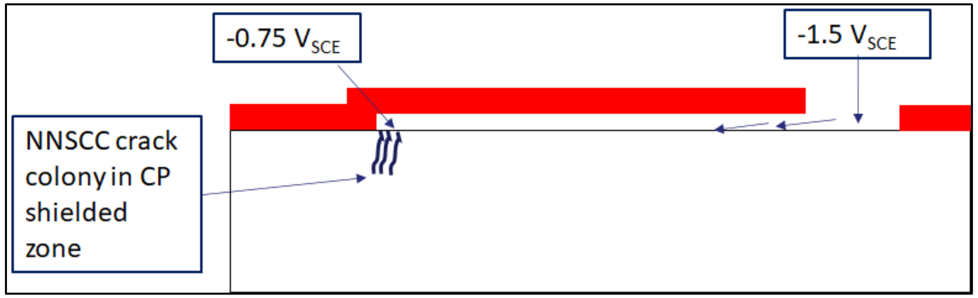
Disbondment size 5 mm = distance between sleeve and bare steel surface

Potential at notch (crack site) located 7 cm from open mouth = open circuit value.

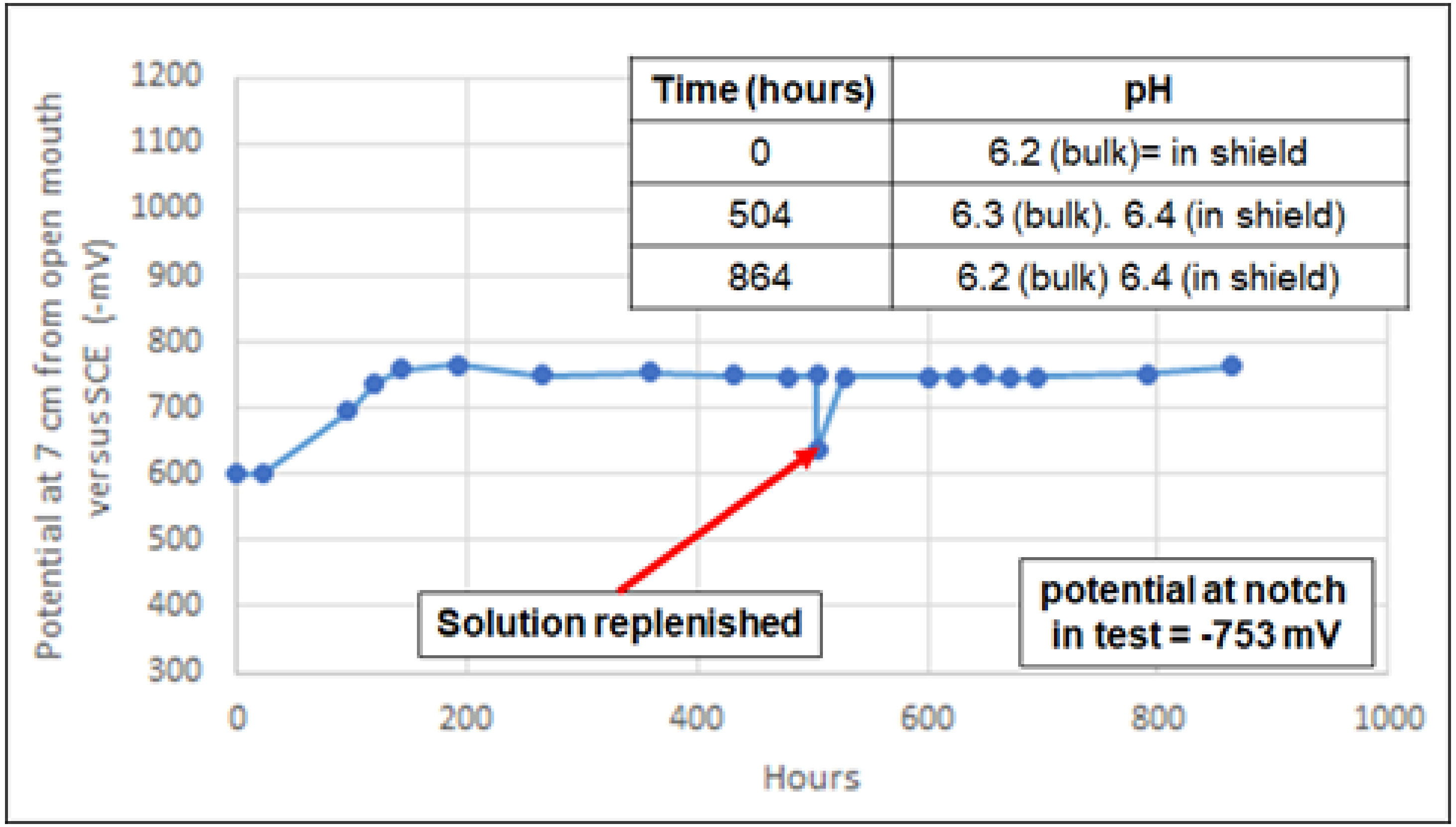
pH in bulk solution and within sleeve also monitored.

Experimental setup (Finishing touches)

- To recreate field situation a flow loop was necessary to feed solution from bulk to sleeve during the tests (3.5 ml/min):



With such a setup it was possible to maintain the NN pH in the disbondment and the potential gradient stable for applied CP down to at least -1.5V.

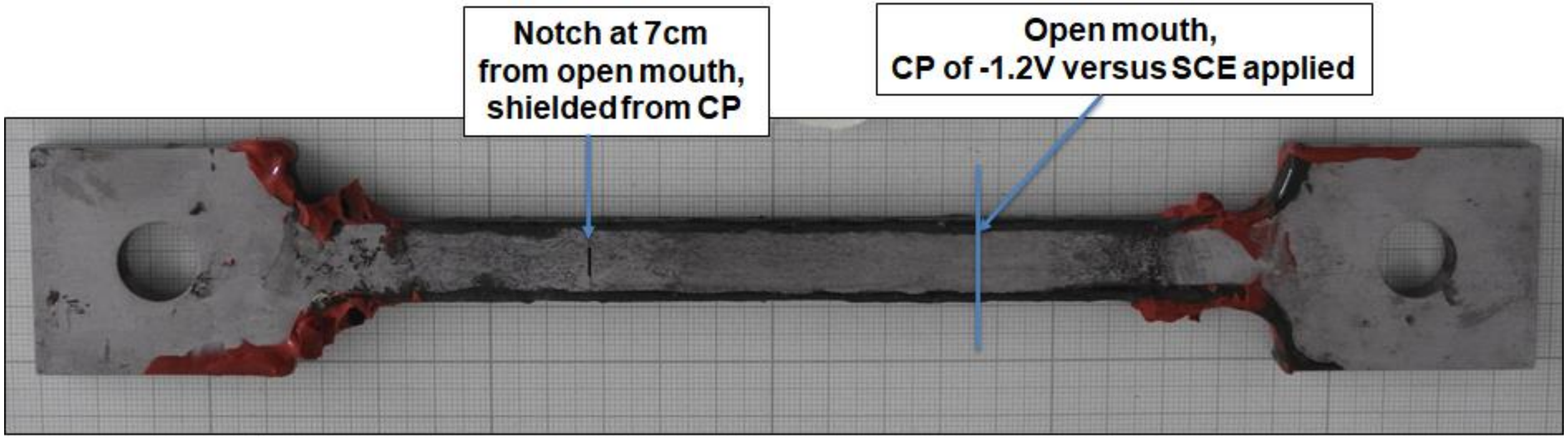


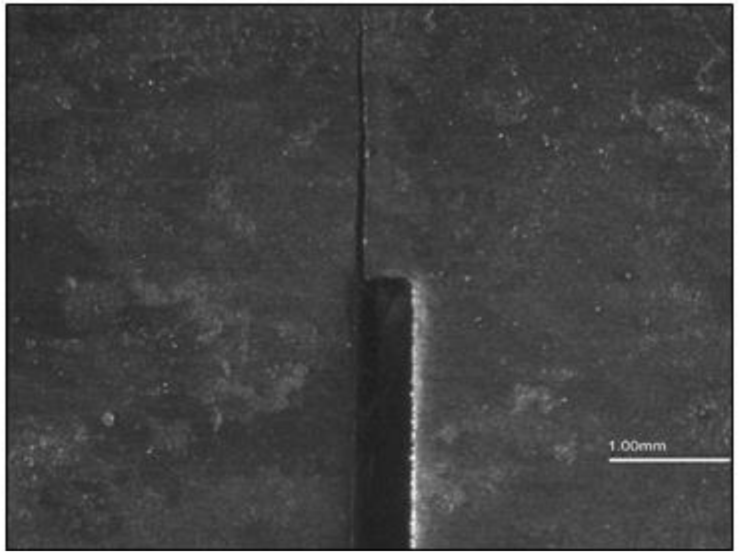
Time (hours)	pH
0	6.2 (bulk)= in shield
504	6.3 (bulk). 6.4 (in shield)
864	6.2 (bulk) 6.4 (in shield)

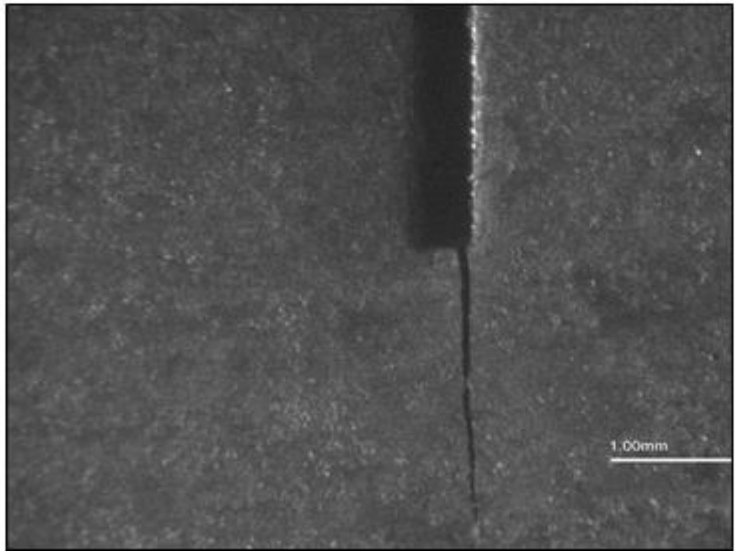
Experimental test plan

- Tests were performed for different potentials at open mouth i.e. $-1.2V_{SCE}$, $-1.5V_{SCE}$ and under open circuit i.e. OCP ($-0.75V_{SCE}$).
- Comparison tests also done in air.
- For each test condition tested 2-3 samples.
- Samples analysed via stereo microscope and SEM.
- Crack growth rates determined i.e. mm of growth in test/ number of cycles = mm/cycle.

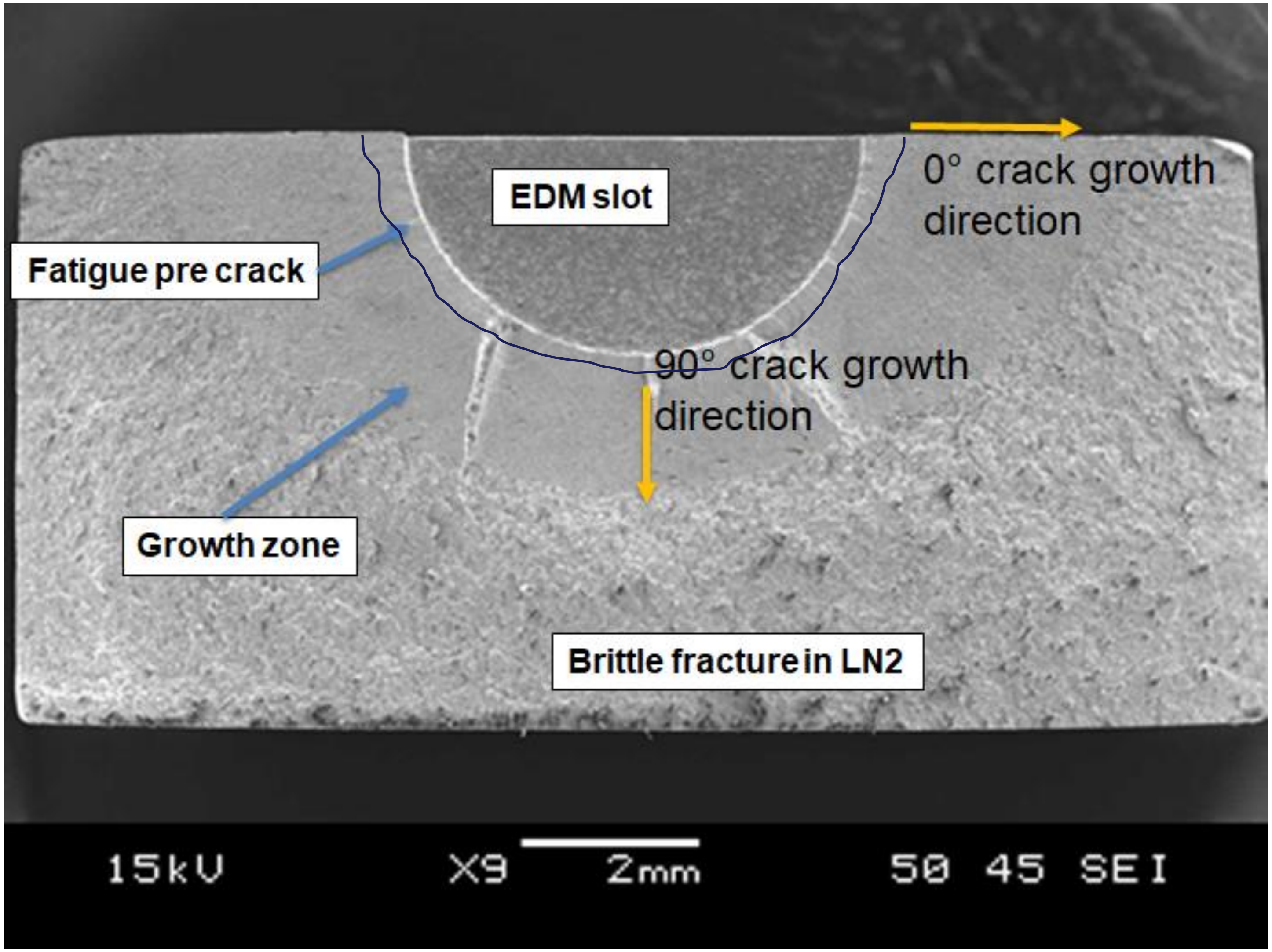
Results: Some examples of sample appearance (1)



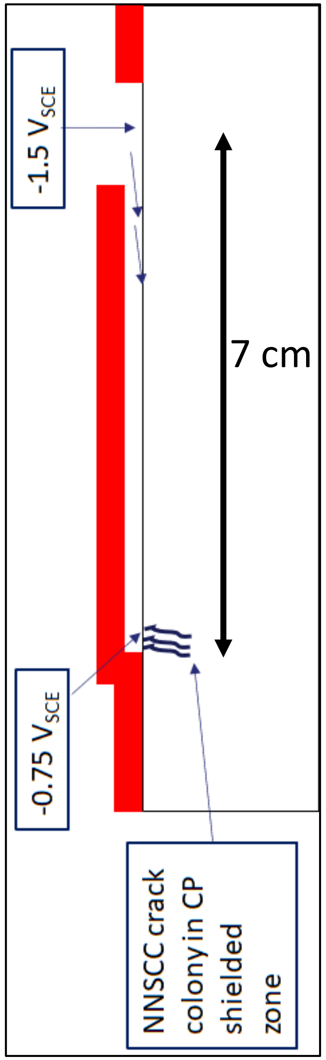


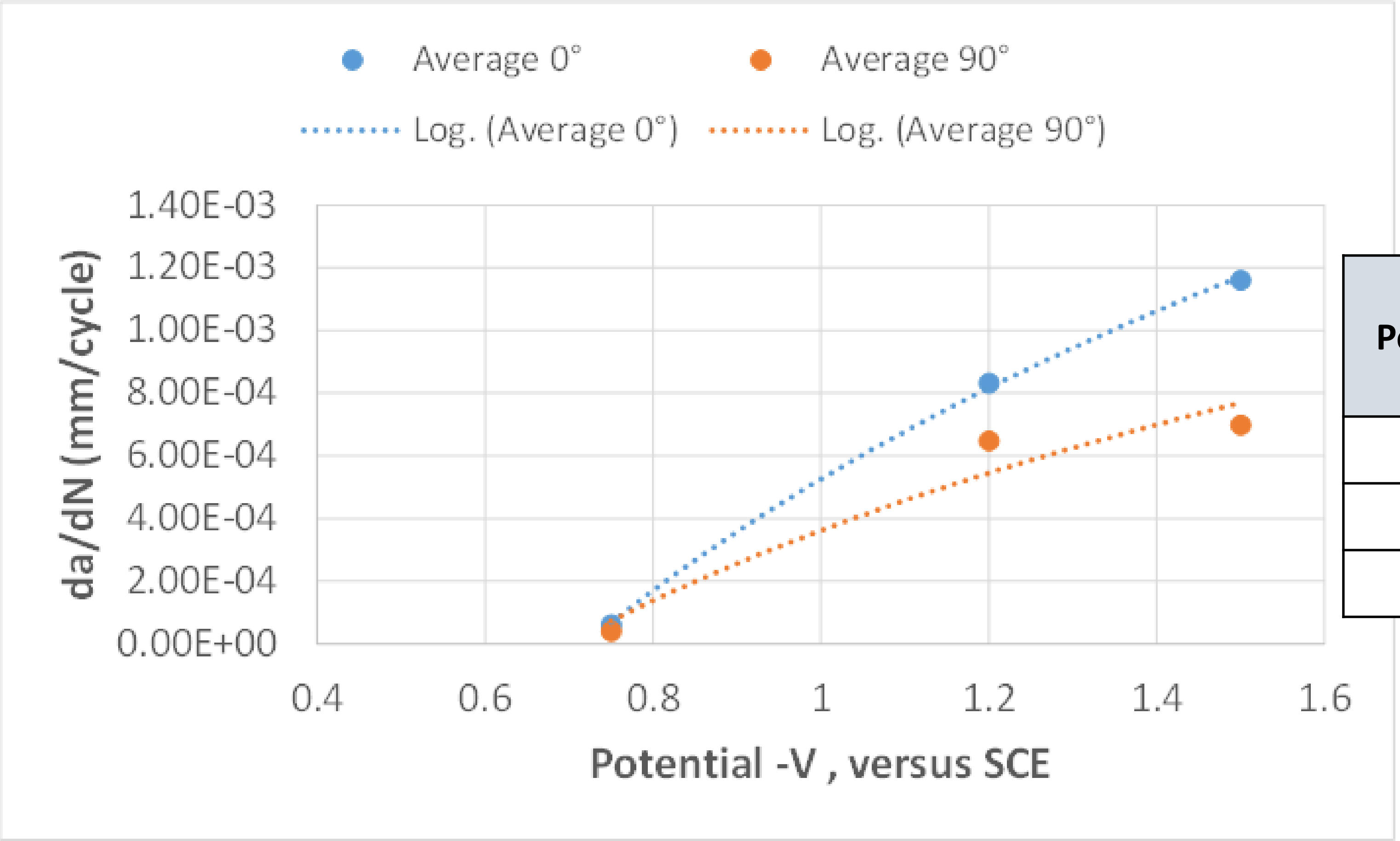


Results: Some examples of sample appearance (2)



Results: Crack growth rates



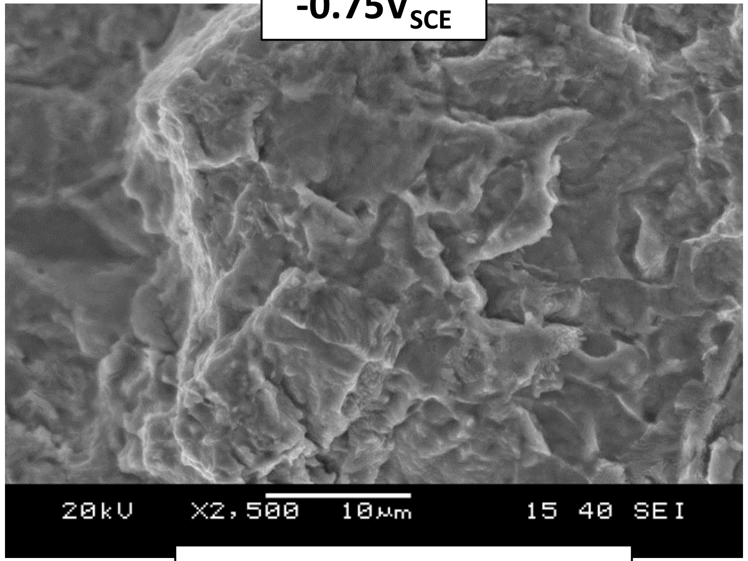


Potential V_{SCE}	(da/dN 90° environment) / (da/dN air)
-0.75	1.2
-1.20	19.7
-1.50	21.3

Results: Example fracture surfaces

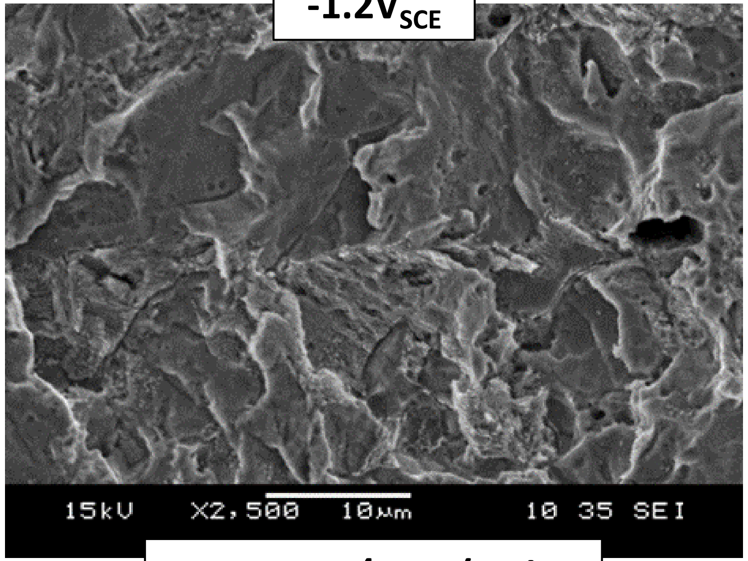
More negative potential

-0.75V_{SCE}



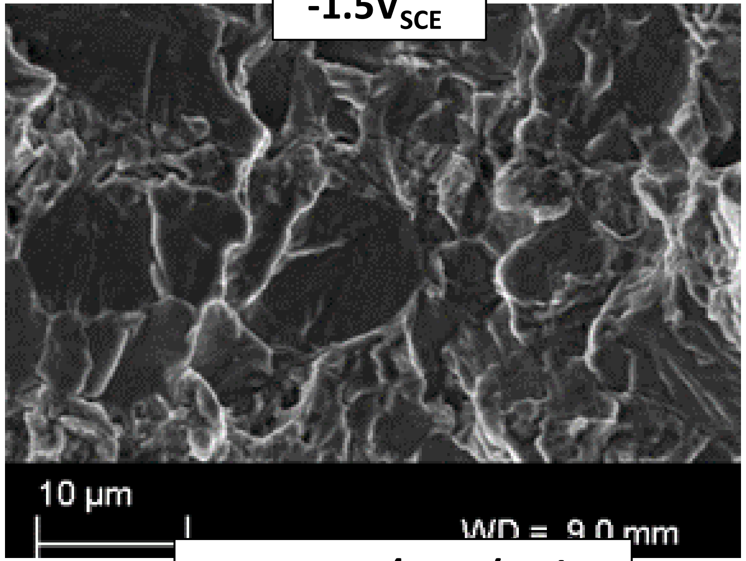
4.39 X 10^{-5} mm/cycle

-1.2V_{SCE}



6.45 X 10^{-4} mm/cycle

-1.5V_{SCE}



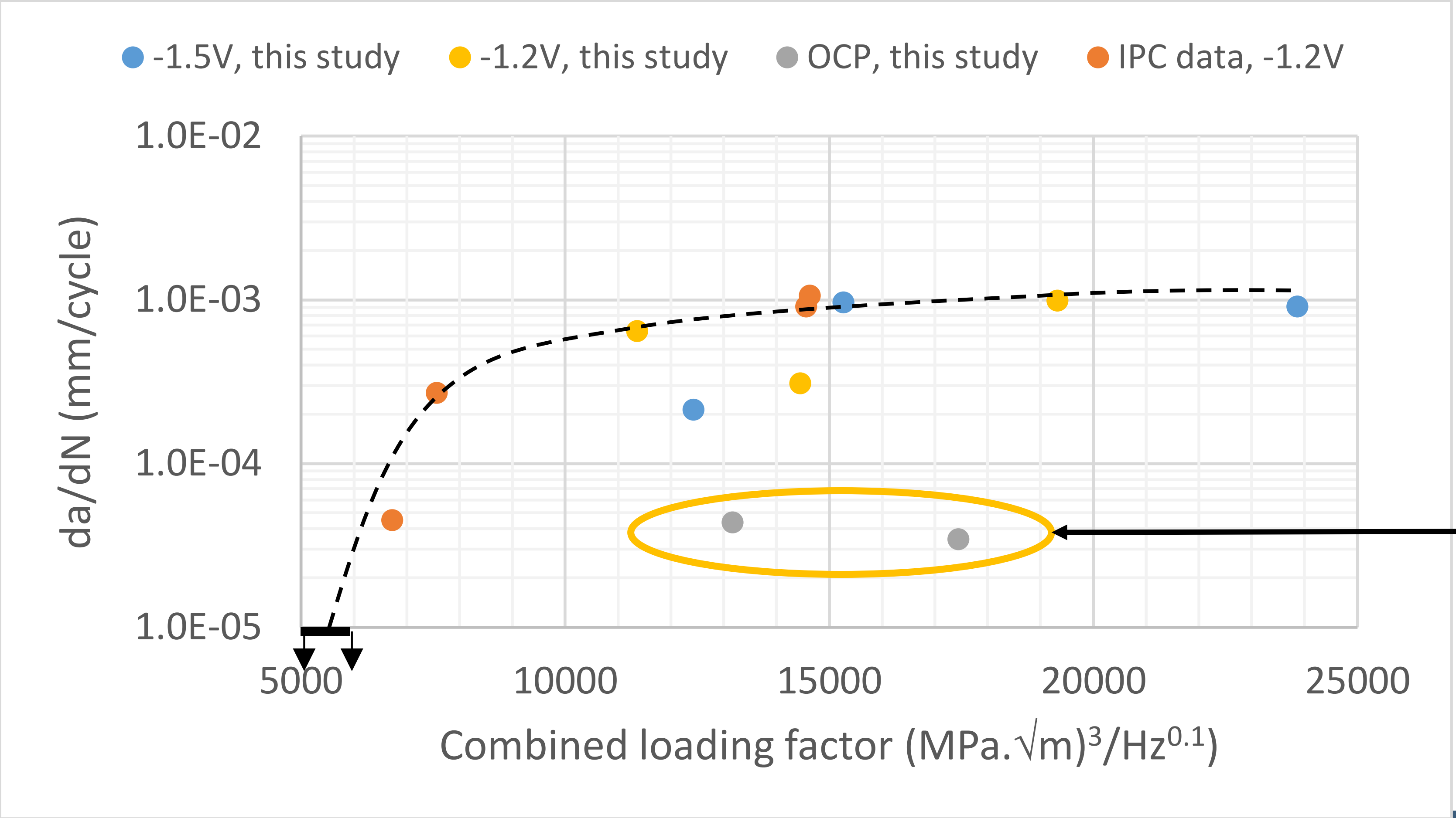
9.14 X 10^{-4} mm/cycle

Increasing crack growth rate

More brittle-like fracture appearance

Discussion: Comparison with published works (1)

- Compare to IPC data [IPC2010 Paper 31436] for X65 + similar microstructure and similar flaw size in same environment.

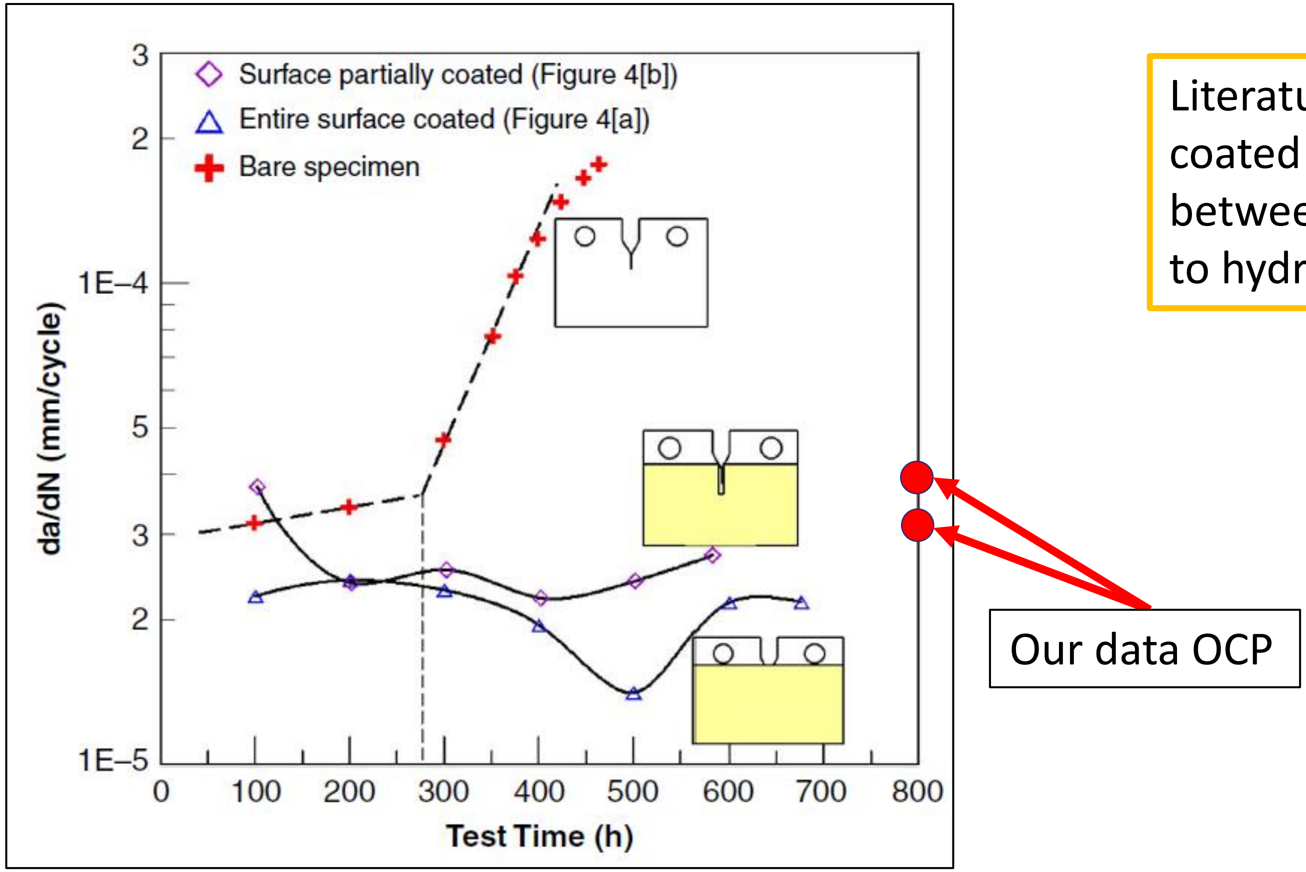


$$CLF = \frac{K_{max}\Delta K^2}{f^{0.1}}$$

Data for OCP condition shows very low crack growth rate- similar to air.

Discussion: Comparison with published works (2)

- Compare OCP data to literature data on compact tension specimens in same solution.



W. Chen, Corrosion, Vol. 72, No.7, (2016), p. 962-977.

Literature data on partially coated CT shows link between da/dN and distance to hydrogen generation sites

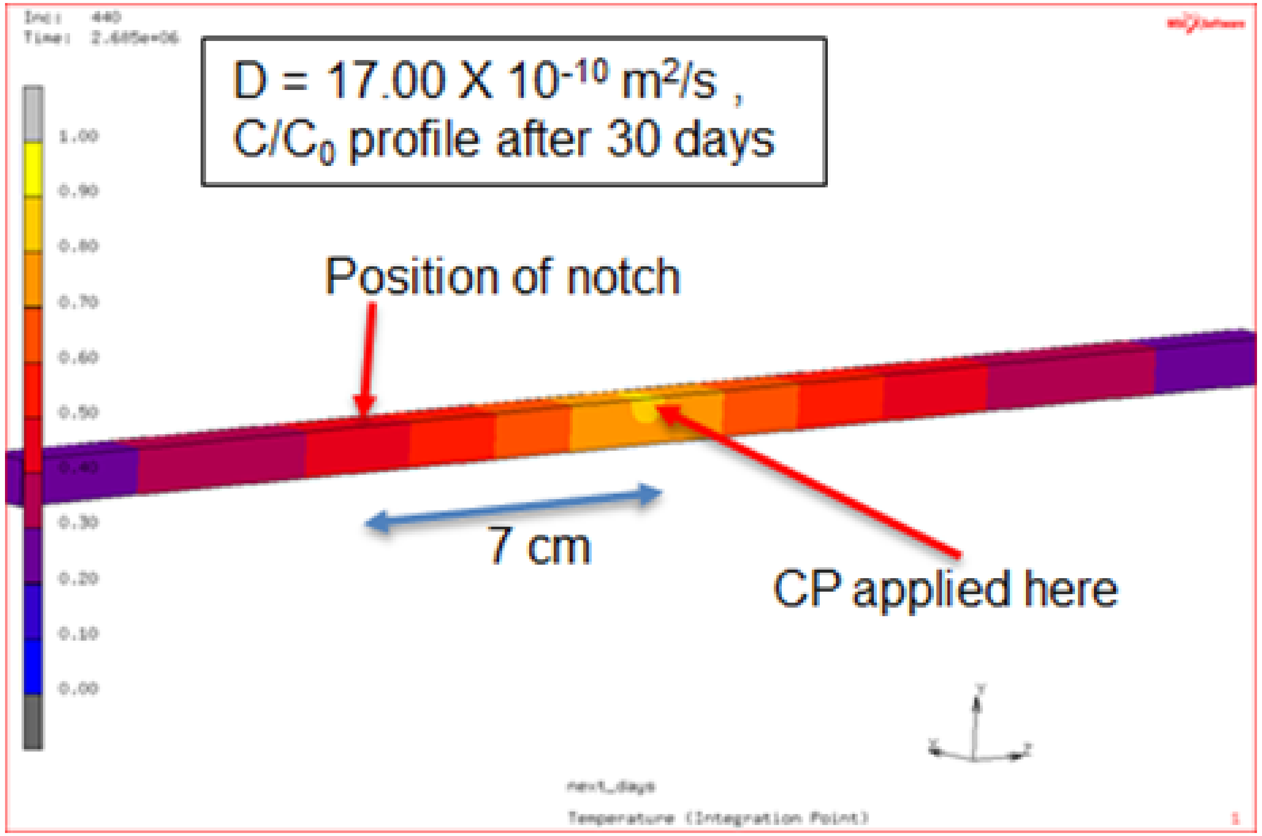
Our data behaves like a partially coated CT

Our specimen has smaller exposed area and crack sides not exposed.

Thus, versus an uncoated CT have little hydrogen generation and accumulation at crack tip.

Discussion: H diffusion to crack from open mouth?

- Our results showed that as potential became more negative at OM, da/dN increased.
- Assuming that long range H is responsible, then diffusion distance must be overcome....



Calcs suggest up to 40% of hydrogen at open mouth position could diffuse 7 cm through steel bulk to crack site within 30 days.

Thus, a significant amount of H can reach the crack during the tests and contribute to the growth rate.

Discussion: Modelling crack growth (1)

- Crack growth model incorporating Hydrogen:

For our data p= 1

$$\frac{da}{dN} = B(K_{max}\Delta K^2 f^{-0.1})^p$$

W. Chen and R. Sutherby, Met. Mater. Trans. A, Vol. 38A, (2007), p. 1260-1268.

For pH = 6.3 = C2 solution

$$C_0 = 10^{-6}\frac{(5+10V)\times 10^{-10}exp\left(-\frac{V}{0.03}\right)}{5+10V-10^{-10}exp\left(-\frac{V}{0.03}\right)}$$

B. Lu, F. Song, M. Gao and M. Elboujdaini, NACE Corrosion (2012), paper No. 01152

- Assuming that diffusion is not rate limiting we can postulate that B simply depends the absorbed atomic hydrogen concentration (C_0) from corrosion (OCP case -0.75V) or from CP (e.g. -1.5V).

Discussion: Modelling crack growth (2)

- From fitting of B values to our data and literature (imposing p = 1), can derive expression relating fitted B to hydrogen content:

$$B = 1.03 \times 10^{-11} ln(C_0) + 4.76 \times 10^{-11}$$

Expression from the current work

Solution	Potential versus SCE (V)	C_0 (ppmw)	B from experiments ($MPa^{-3}m^{-0.5}s^{-0.1}$)	B from equation ($MPa^{-3}m^{-0.5}s^{-0.1}$)
C2 (pH = 6.3)	-0.75 (Work of Chen et al on CT specimens)	0.39	3.86×10^{-11}	3.80×10^{-11}
C2 (pH = 6.3)	-1.2 (this work)	0.98	4.51×10^{-11}	4.74×10^{-11}
C2 (pH = 6.3)	-1.5 (this work)	1.36	5.25×10^{-11}	5.08×10^{-11}

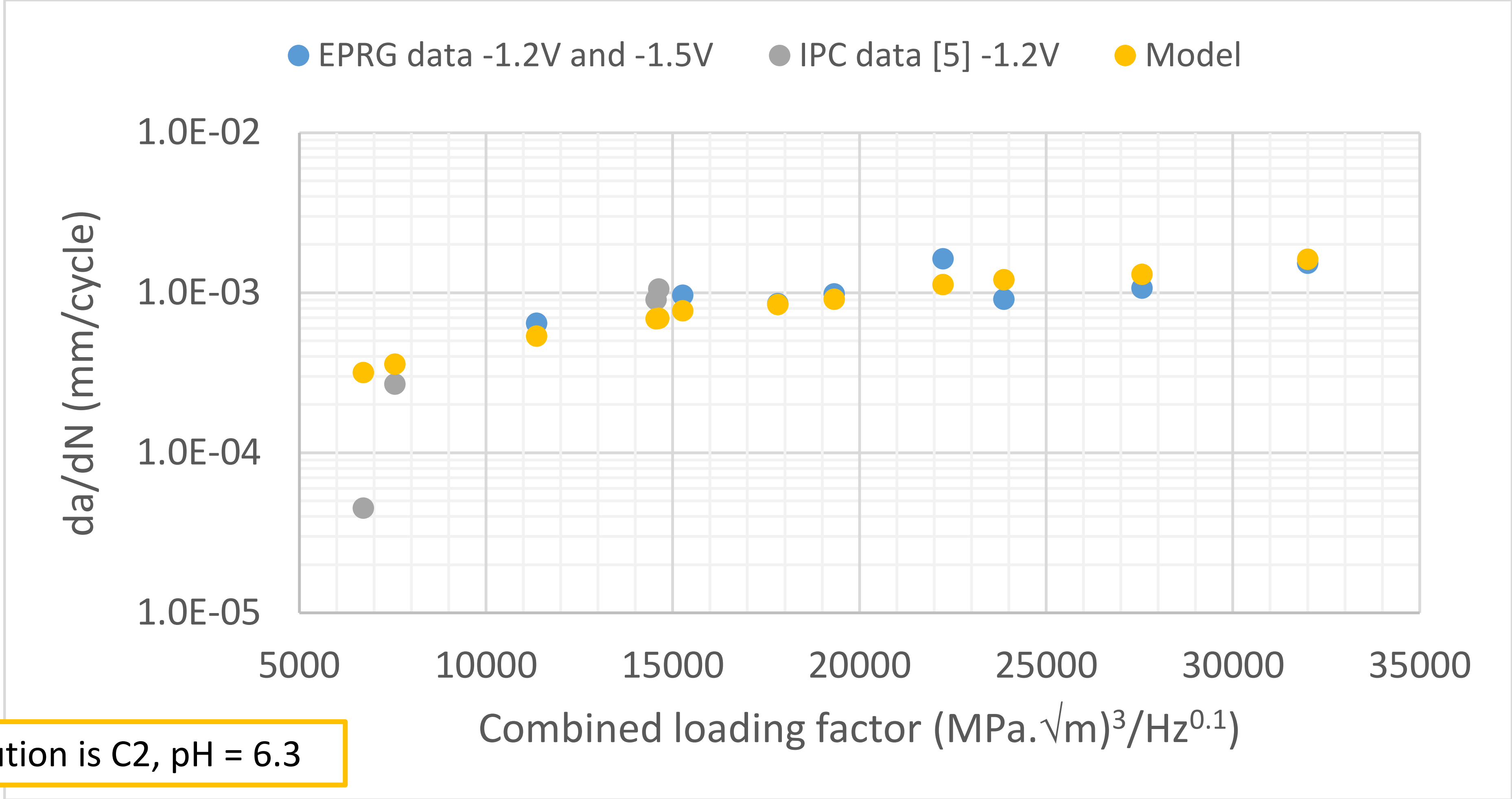
Note that B derived from expts increases with C0- showing that B does depend on hydrogen

$$\frac{da}{dN} = [1.03 \times 10^{-11} ln(C_0) + 4.76 \times 10^{-11}][K_{max} \Delta K^2 f^{-0.1}]$$

Final model from the current work

Discussion: Modelling crack growth (3)

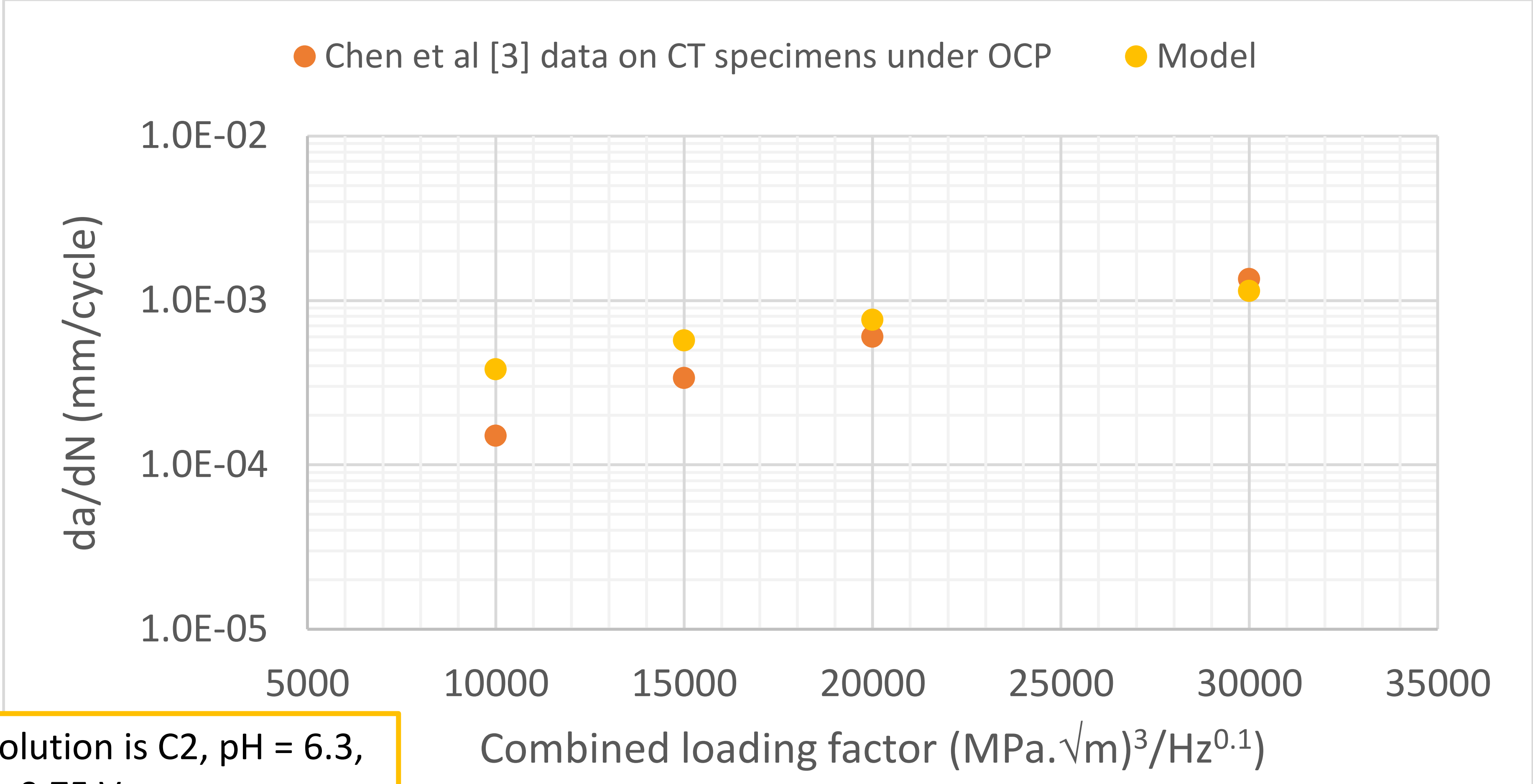
- Comparison of model with our data and IPC paper data (same specimen type):



Test solution is C2, pH = 6.3

Discussion: Modelling crack growth (4)

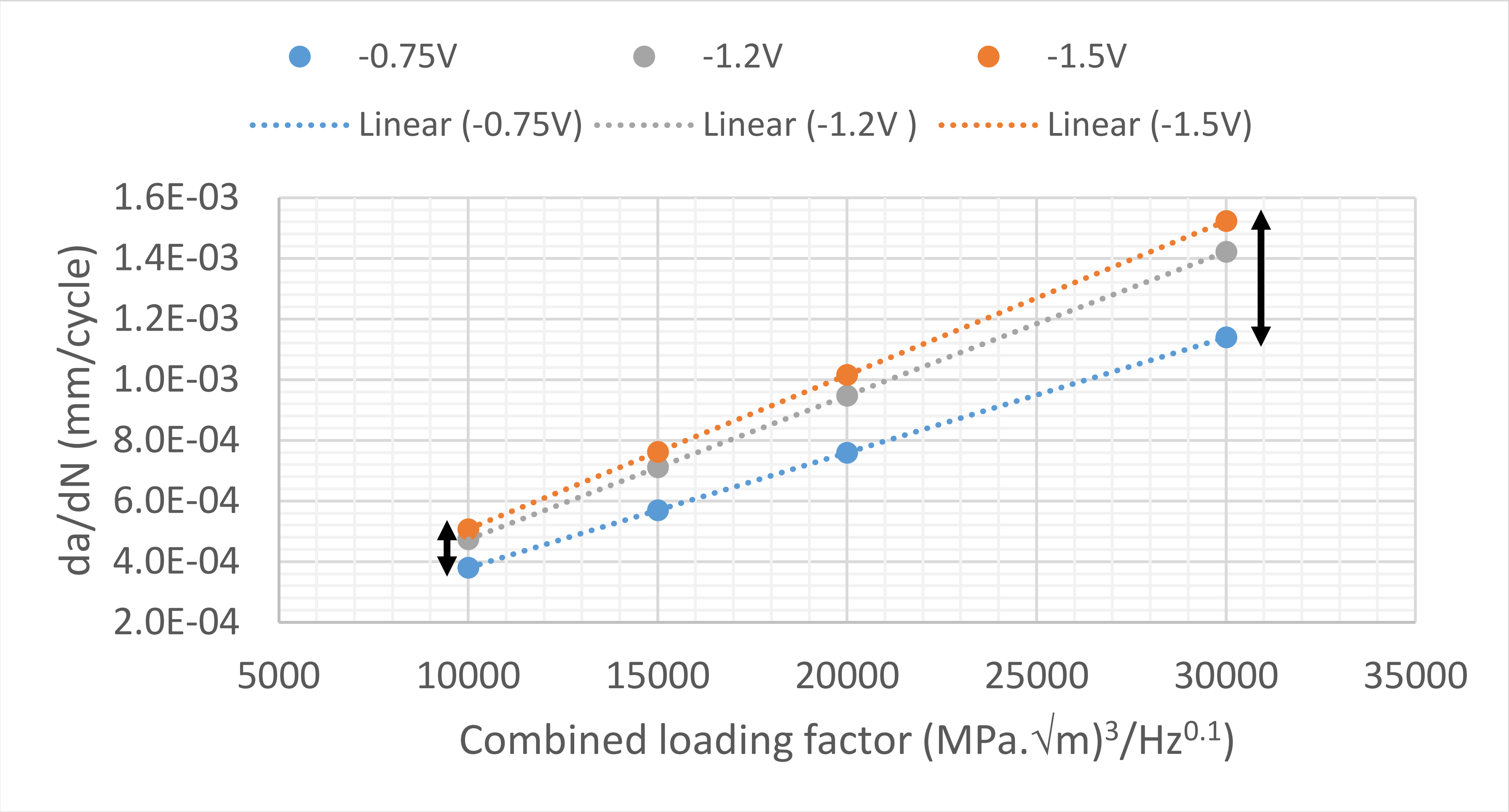
- Comparison of model with literature data (compact tension specimens):



Test solution is C2, pH = 6.3, OCP =-0.75 V_{SCE}

Discussion: Modelling crack growth (5)

- Model trends considering effect of combined loading factor and potential:



More negative potential gives more C_0 and faster crack growth

Synergy with mechanical fatigue is evident- comparing da/dN at low and high CLF.

Conclusions (1)

- Low crack growth rates (comparable to tests in air) were observed for samples tested under OCP (-0.75V_{SCE}).

- Applying CP potentials at the open mouth(-1.2V and -1.5V_{SCE}) led to a remarkable increase in the (shielded) crack growth rate, i.e. 20 times higher than that seen in air.

- Comparison of crack growth rates with limited literature (-1.2V_{SCE}) for same specimen geometry gave good agreement, after accounting for mechanical loading factor effects.

- For the OCP case the crack growth rates were much lower than literature data from compact tension specimens.

Conclusions (2)

- This was explained to be due to differences in specimen geometry i.e. hydrogen accumulation at the crack tip was favoured for CT specimens.

- The experiments and modelling work showed that crack growth was driven by hydrogen at the crack tip in synergy with mechanical fatigue.

- The main source of hydrogen was provided by the CP at the open mouth. Diffusion calculations supported the idea of long range diffusion of hydrogen to the crack site.

- A simple model was developed from the current data with CP + literature for CT specimens under OCP:

$$\frac{da}{dN} = [1.03 \times 10^{-11} ln(C_0) + 4.76 \times 10^{-11}][K_{max} \Delta K^2 f^{-0.1}]$$

Thank you for your attention.