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Reducing the Risk of NNpH SCC Failure through Operation Pressure Optimization

07 June 2022

Project Team and Sponsors

Reducing the Risk of NNpH SCC Failure through Operation Pressure Optimization

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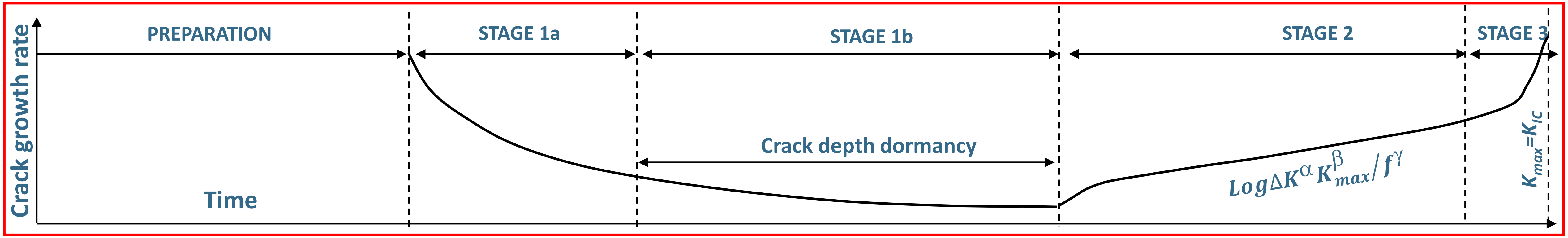
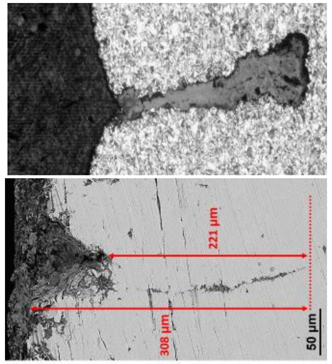
TC Energy, Calgary AB, CA

Overview of effect of pressure fluctuations (PFs)

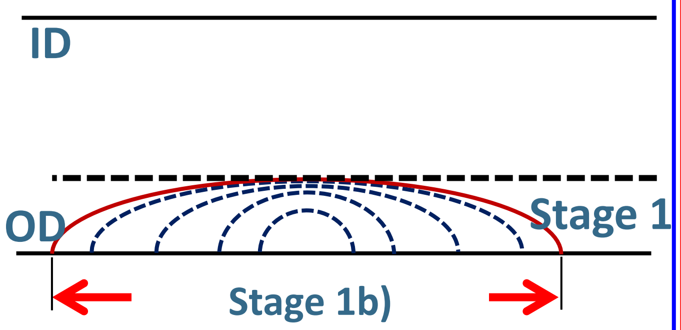


Preparation stage

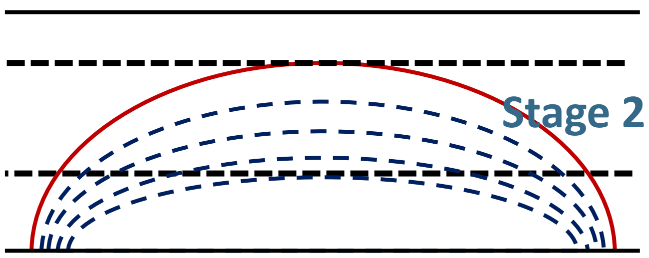
- Formation of mill scale
- Cracking of mill scale
- Introduction of residual stresses (mechanical damage, pipe bend, soil movement)
- Coating damage and Ground water access
- Hydrotesting
- Discontinuous yielding



Crack initiation (1a)



Early-stage crack growth (1b)

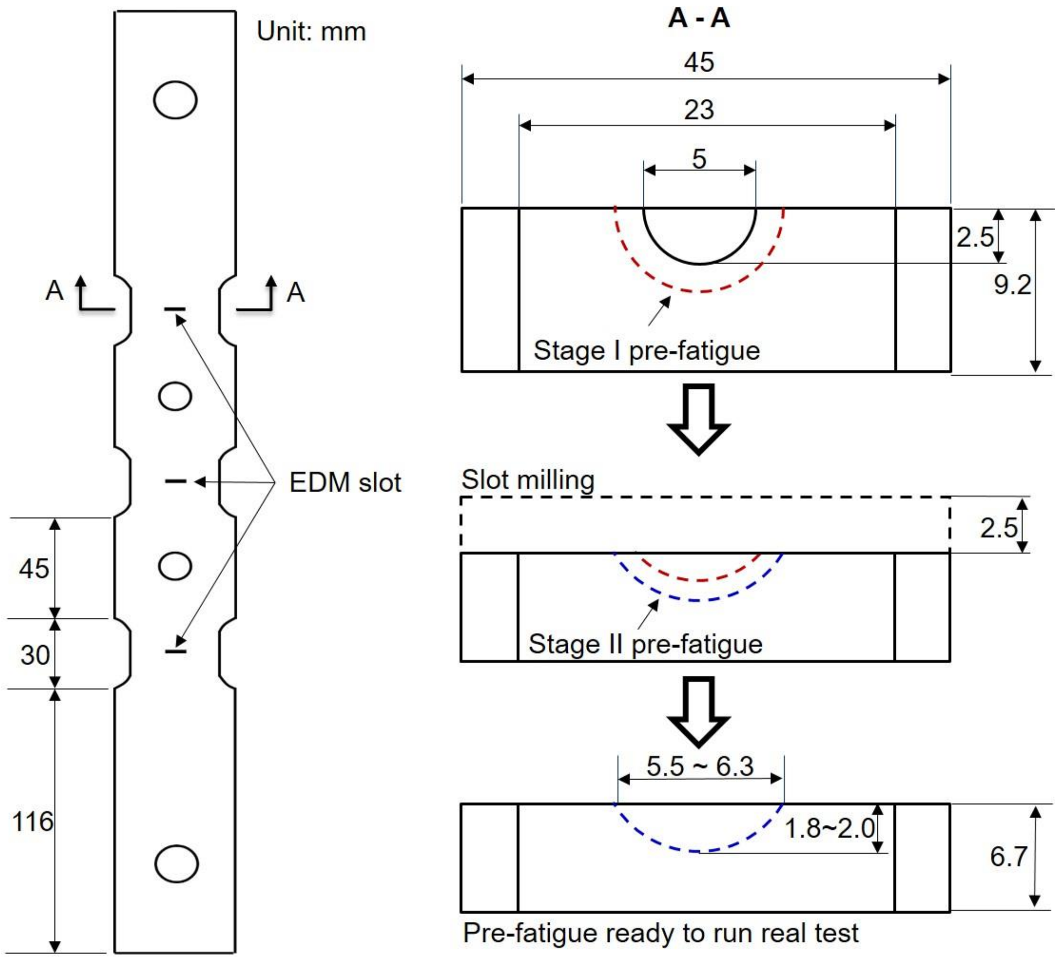


Steady stage growth (2)

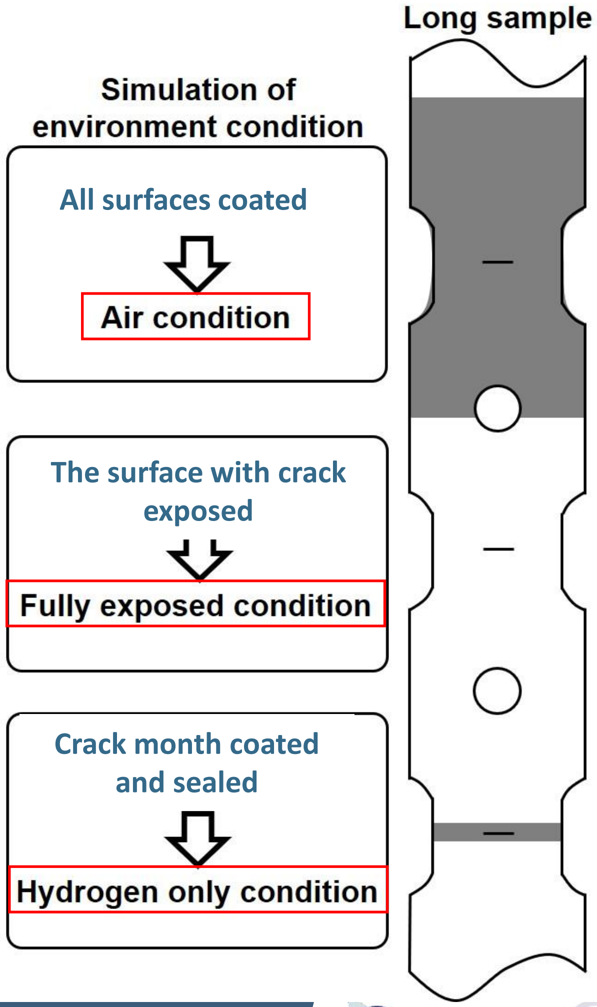
EFFECT OF PRESSURE

Overview of experimental methodology

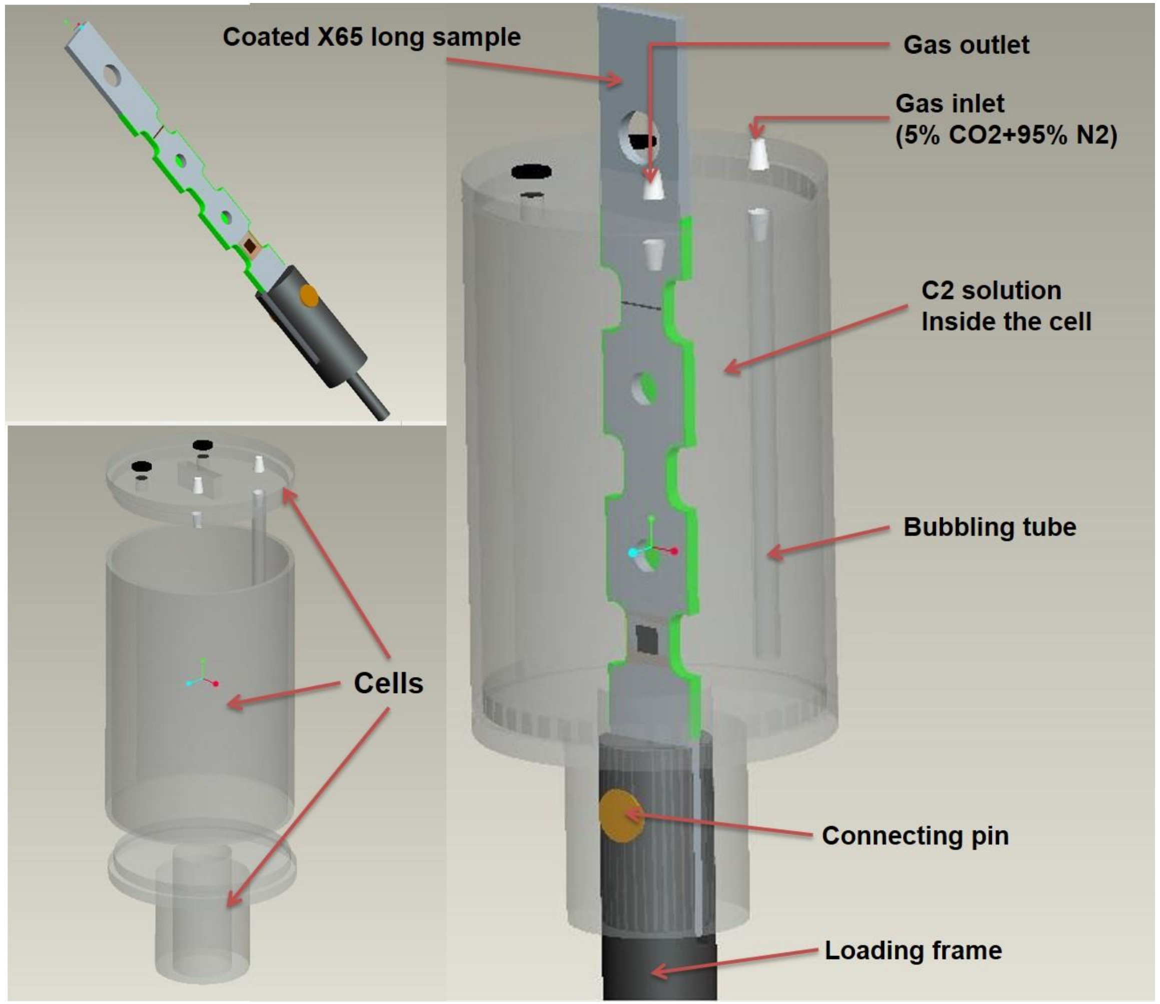
Sample dimension and processes to make specimens with sharp surface cracks



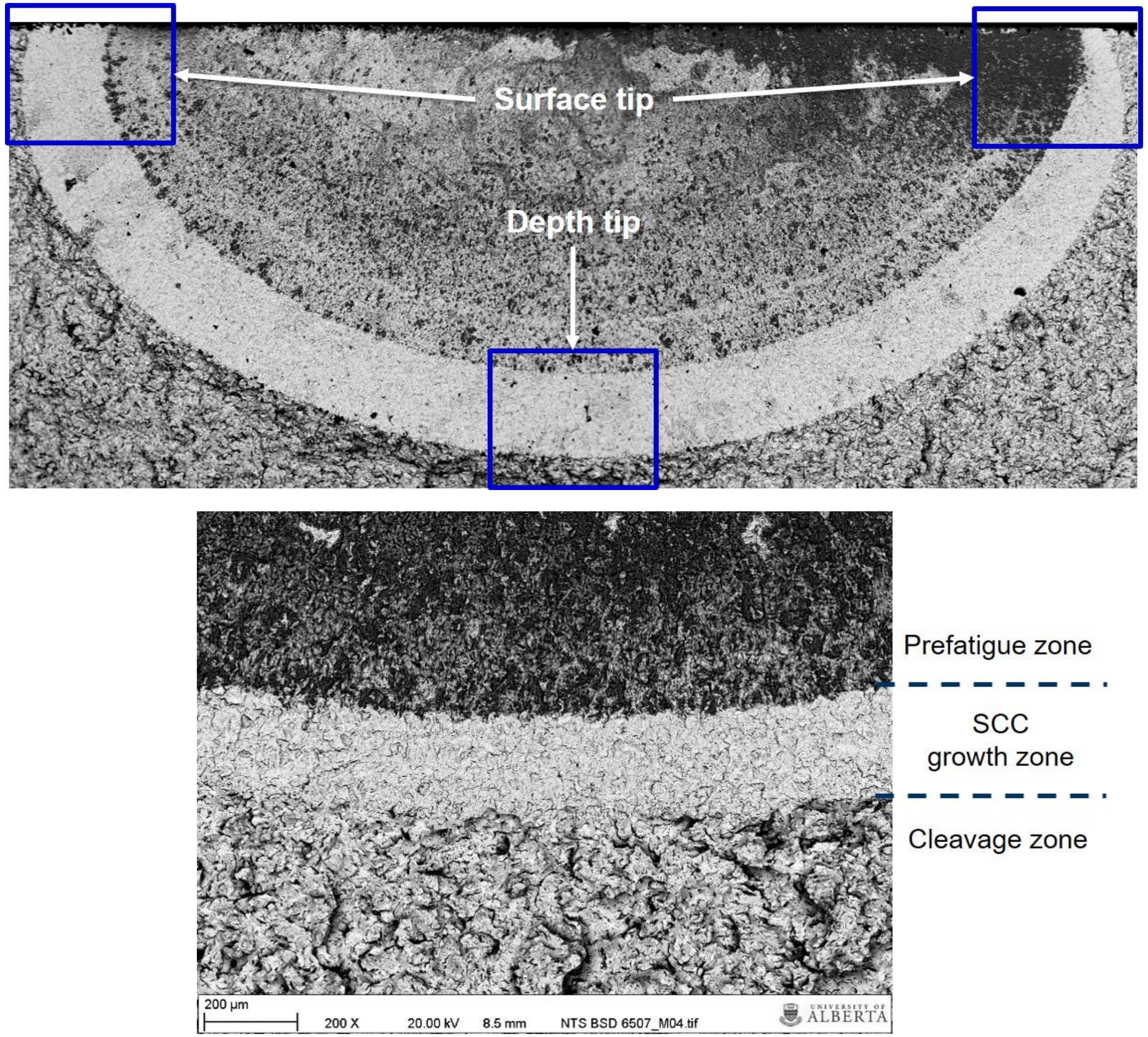
Environmental conditions



Overview of experimental methodology



Schematic diagram of test cell set up

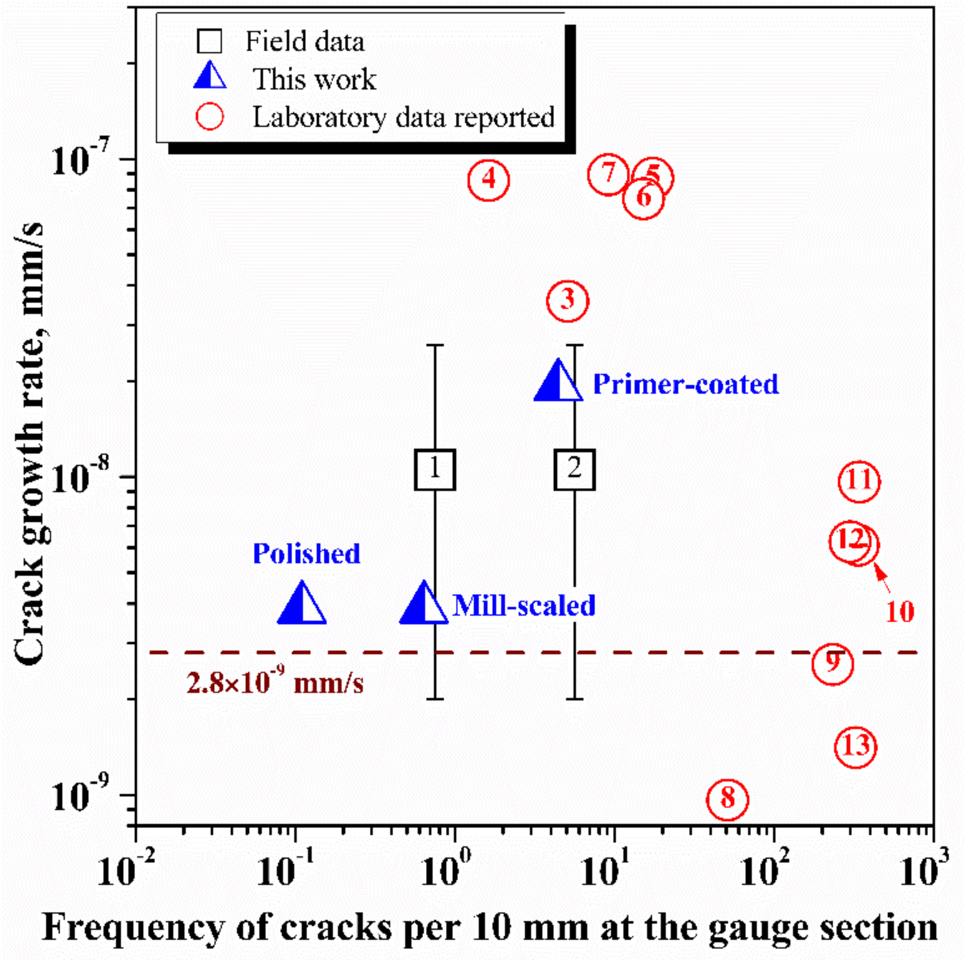


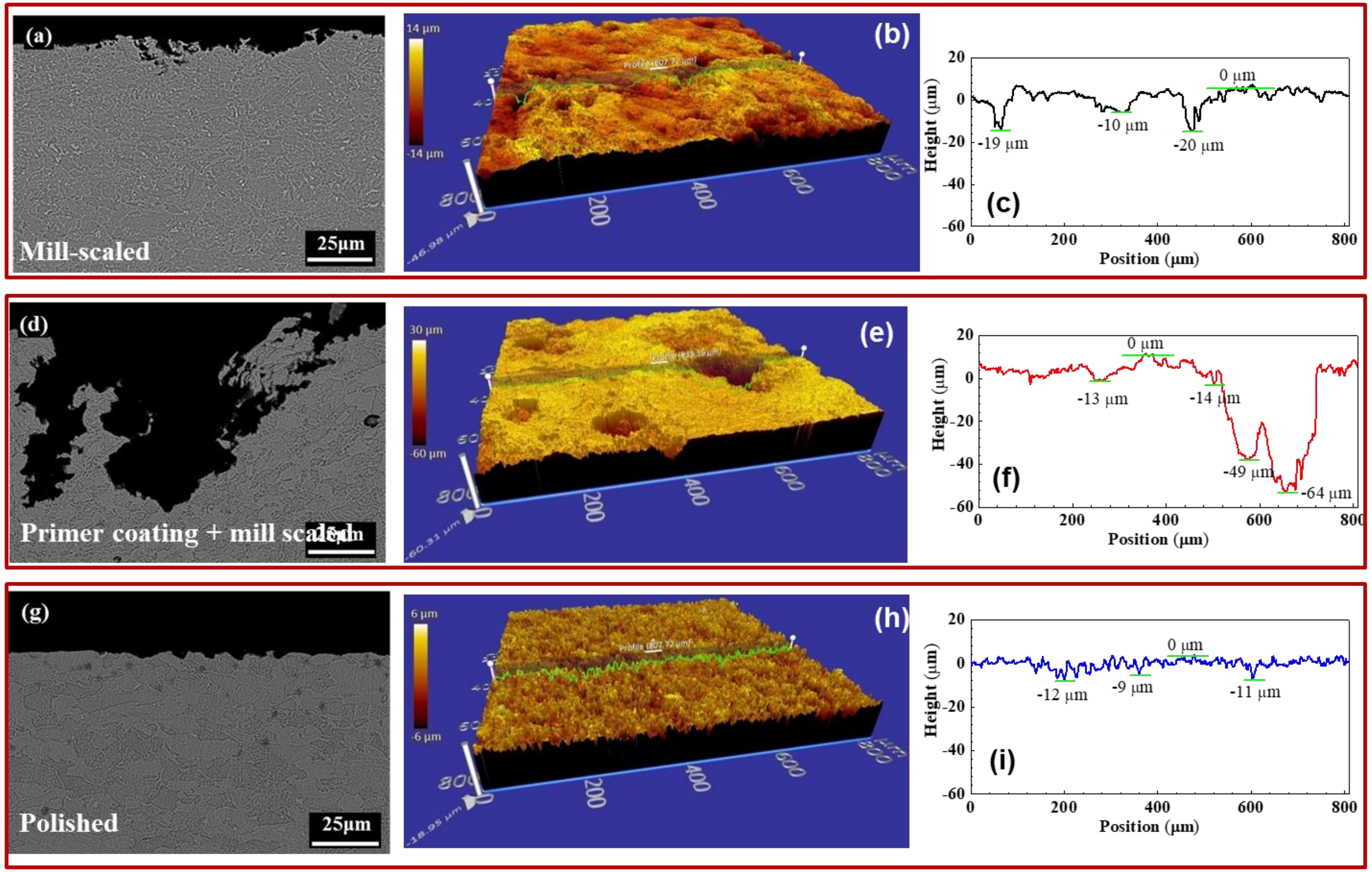
Surface/depth crack growth measurement

Outline of major results obtained

1. Increased risk of crack initiation caused by pressure fluctuations
2. Increased risk of crack growth in early-stage initiation caused by pressure fluctuation
3. Increased risk of crack growth in Stage 2 caused by pressure fluctuation
4. Contribution to crack growth by corrosion affected by pressure fluctuations
5. Crack Growth under variable amplitude loading
6. Validation of crack growth models by full scale testing
7. Probability of crack growth affected by pressure fluctuation
8. *PipeOnline* software for crack growth rate calculation and remaining life assessments
9. Operation pressure optimization to reduce the risk of NNpH SCC failure
10. Summary and conclusions

1. Increased risk of crack initiation caused by PFs

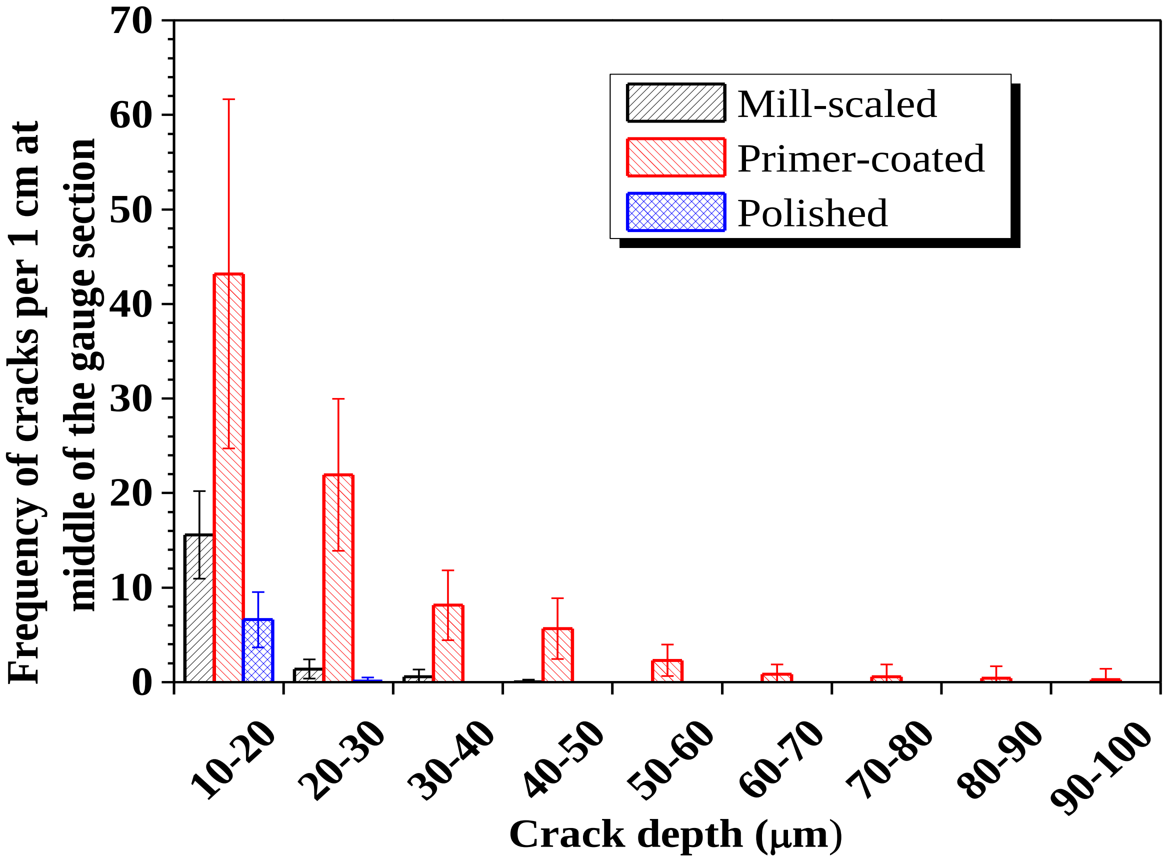


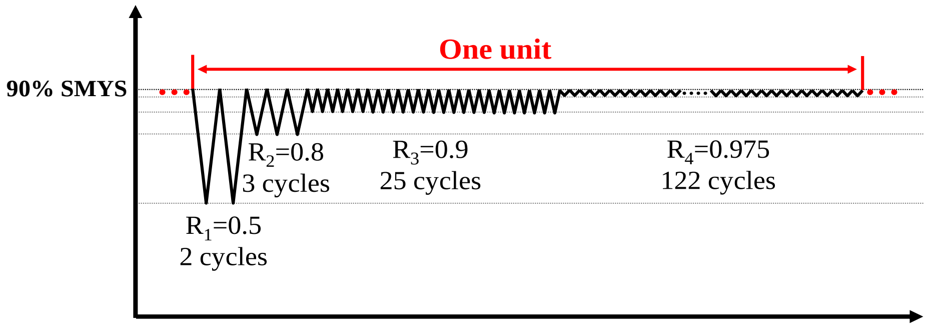


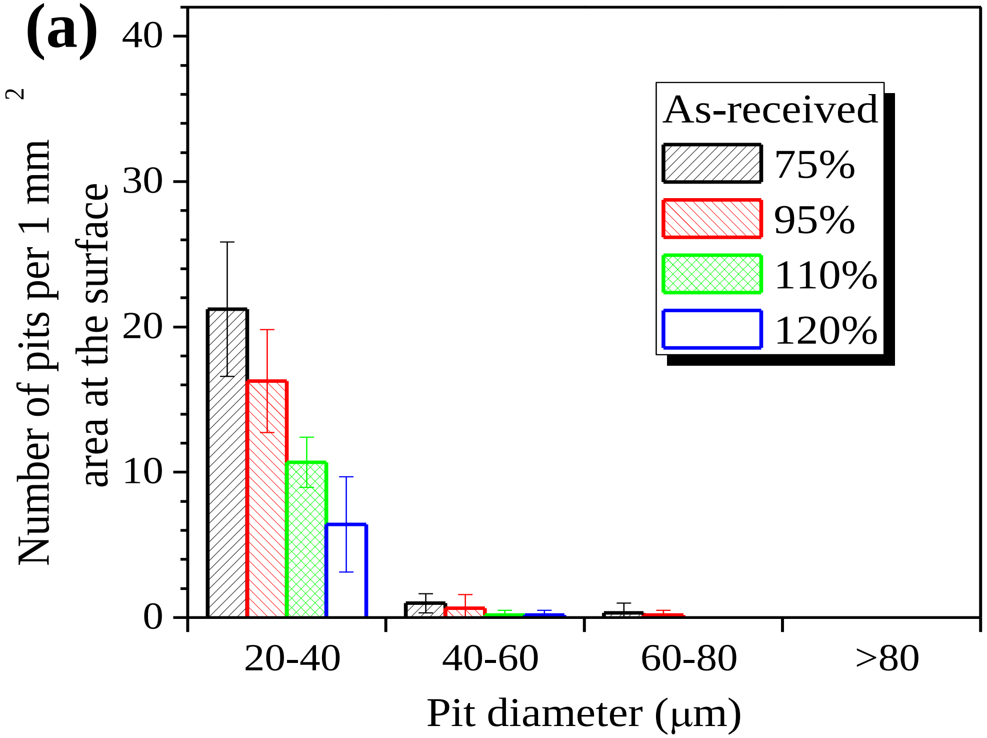
Shidong Wang, Lyndon Lamborn, Karina Chevil, Erwin Gamboa, Weixing Chen, DENSE AND SPARSE STRESS CORROSION CRACK INITIATION IN AN X65 PIPELINE STEEL WITH MILL SCALE, Proceedings of the 13th International Pipeline Conference, IPC 2020, September 28 – October 02, 2020, Calgary, Alberta, Canada, Paper # IPC2020-9510

Wang, S., Lamborn, L., Chevil, K., Gamboa, E., Chen, W., On the formation of stress corrosion crack colonies with different crack population, Corrosion Science, Volume 168, 15 May 2020, Article number 108592 (14 pages)

1. Increased risk of crack initiation caused by PFs







The frequency of pits statistically analyzed on 1 cm length at the middle of the gauge section with different depths for specimens

Wang, S., Lamborn, L., Chevil, K., Gamboa, E., Chen, W., On the formation of stress corrosion crack colonies with different crack population, Corrosion Science, Volume 168, 15 May 2020, Article number 108592 (14 pages)

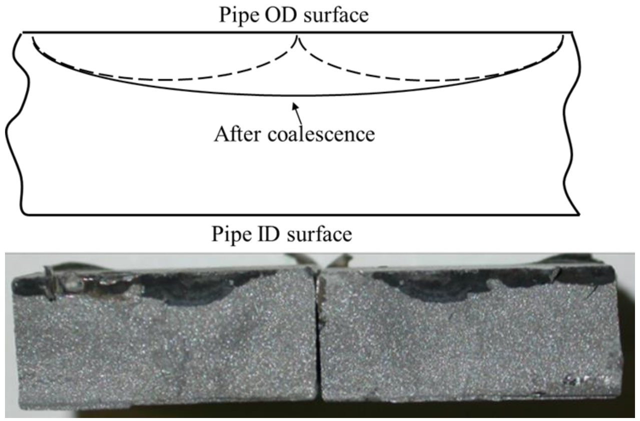
2. Incrsd risk of early-stage crack initiation & growth by PFs

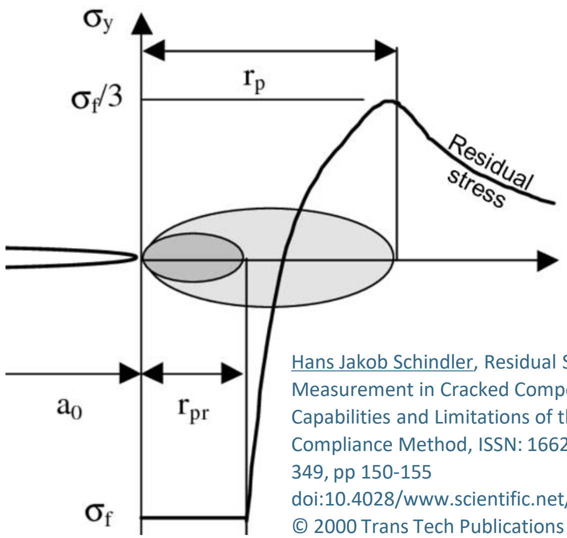
Three ways of crack length extension:

a) Geometry of the coating disbondment dependent

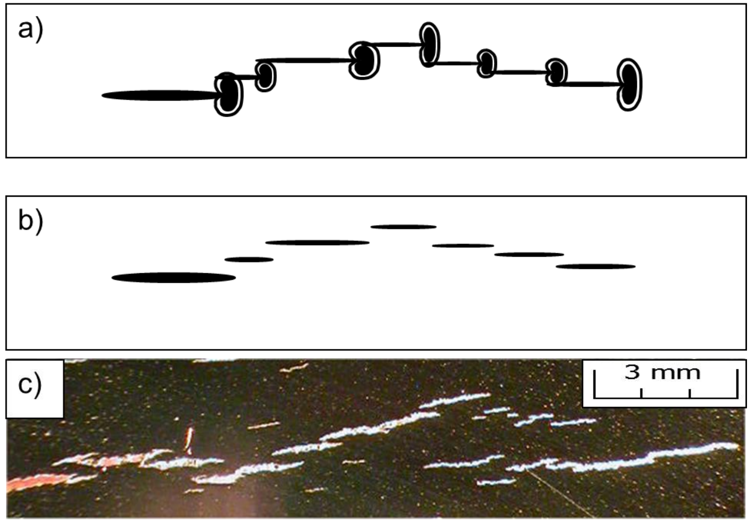
b) Stochastic process of crack coalescence

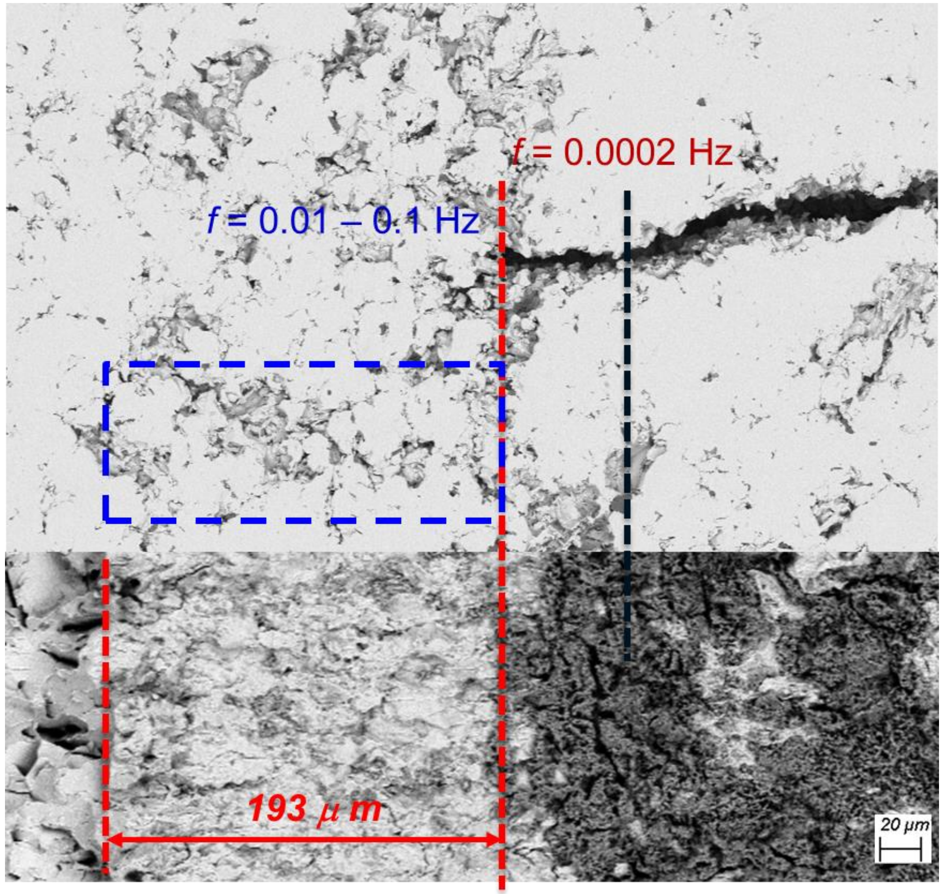
c) Existing crack induced initiation and growth, which is pressure fluctuation dependent





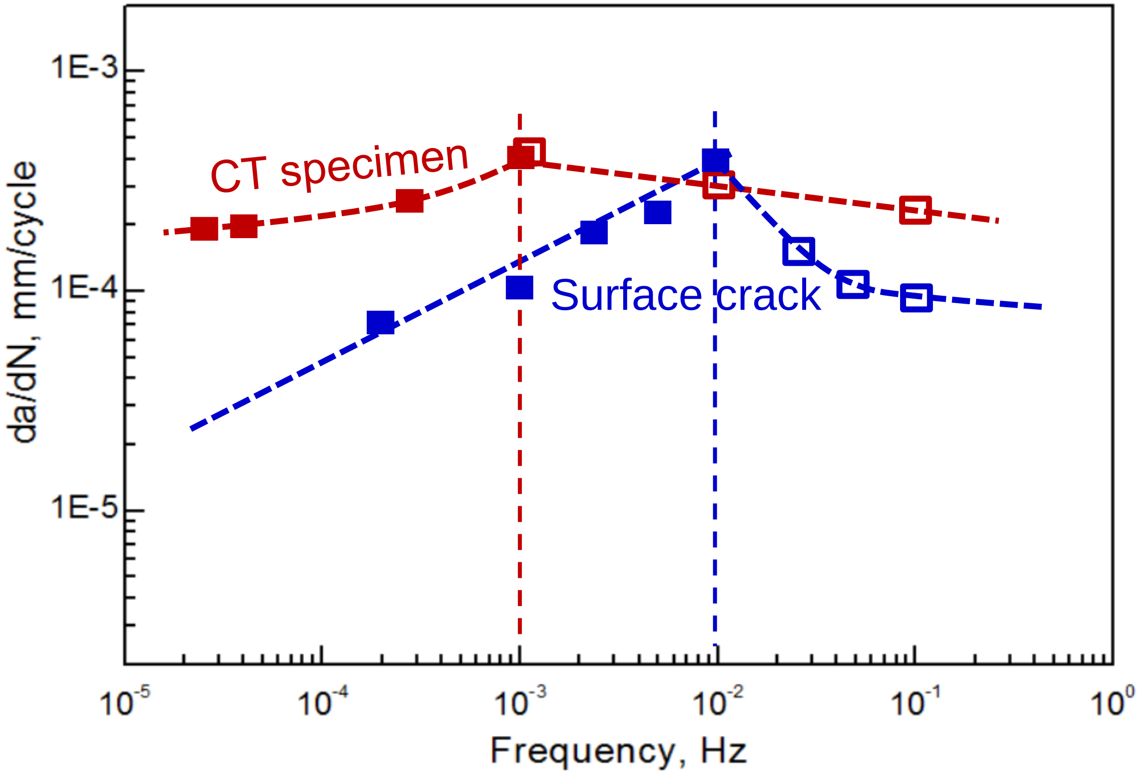
Hans Jakob Schindler, Residual Stress Measurement in Cracked Components: Capabilities and Limitations of the Cut Compliance Method, ISSN: 1662-9752, Vols. 347-349, pp 150-155 doi:10.4028/www.scientific.net/MSF.347-349.150

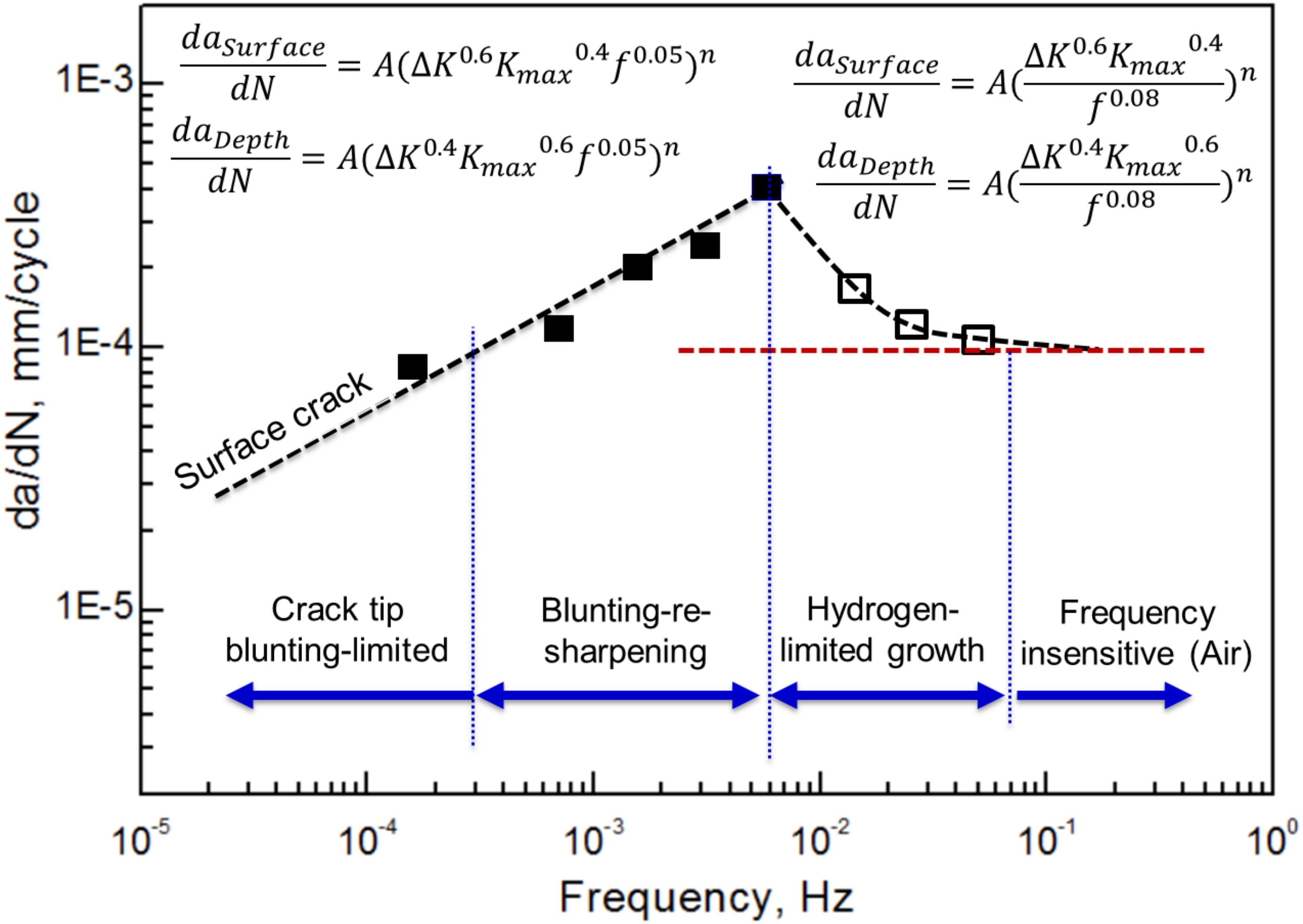




3. Incrsd risk of early-stage crack initiation & growth by PFs

	Oil pipelines	Gas pipelines
# of underload cycles	537/year	8/year
Unloading frequency	$6.89\times10^{-6} \sim 1.0\times10^{-1}$ Hz	$1.30\times10^{-6} \sim 9.16\times10^{-5}$ Hz
Loading frequency	$5.11\times10^{-6} \sim 1.0\times10^{-2}$ Hz	$1.34\times10^{-6} \sim 5.26\times10^{-6}$ Hz

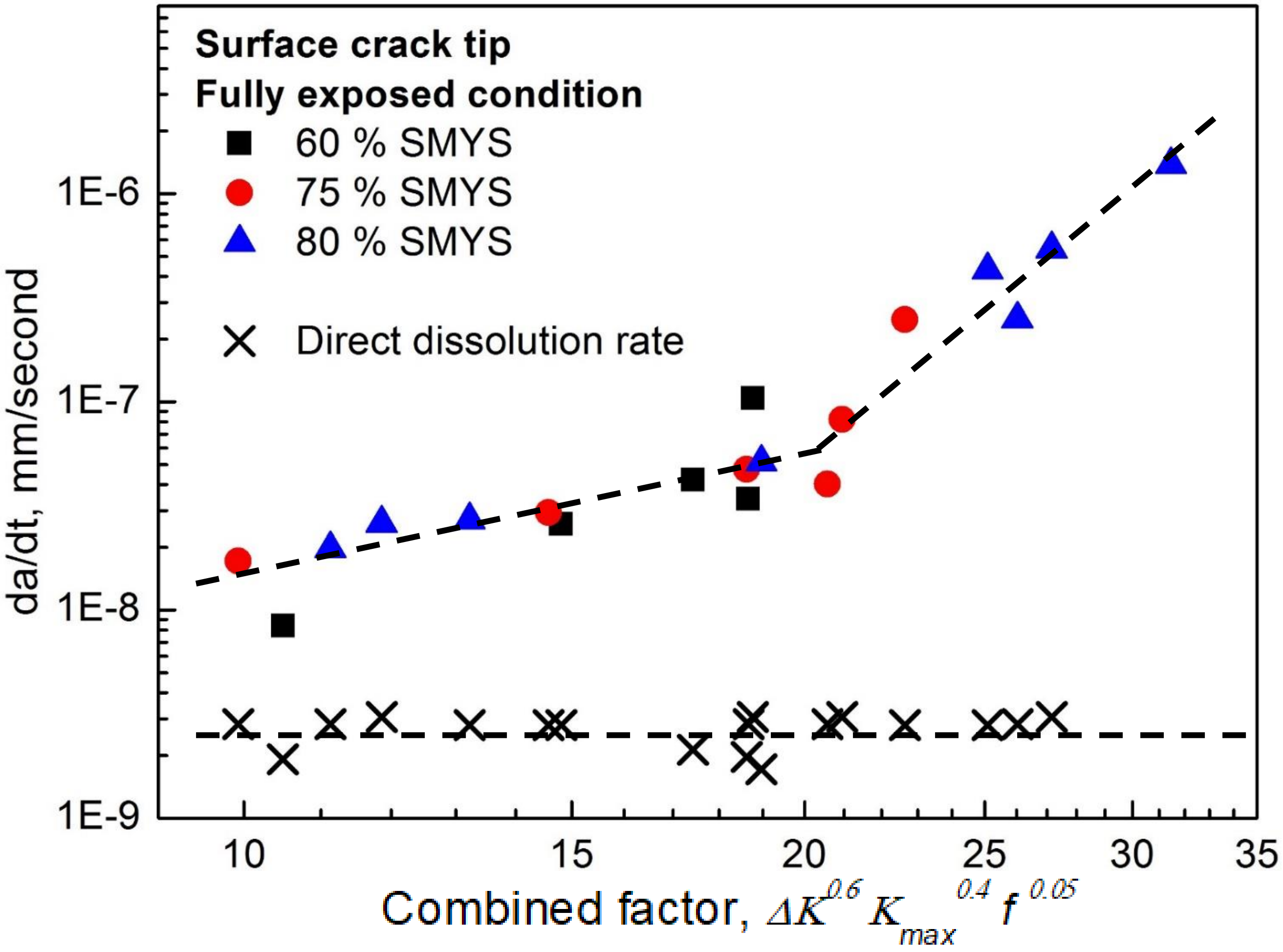




In fully exposed condition

4. Contribution to crack growth by corrosion affected by PFs

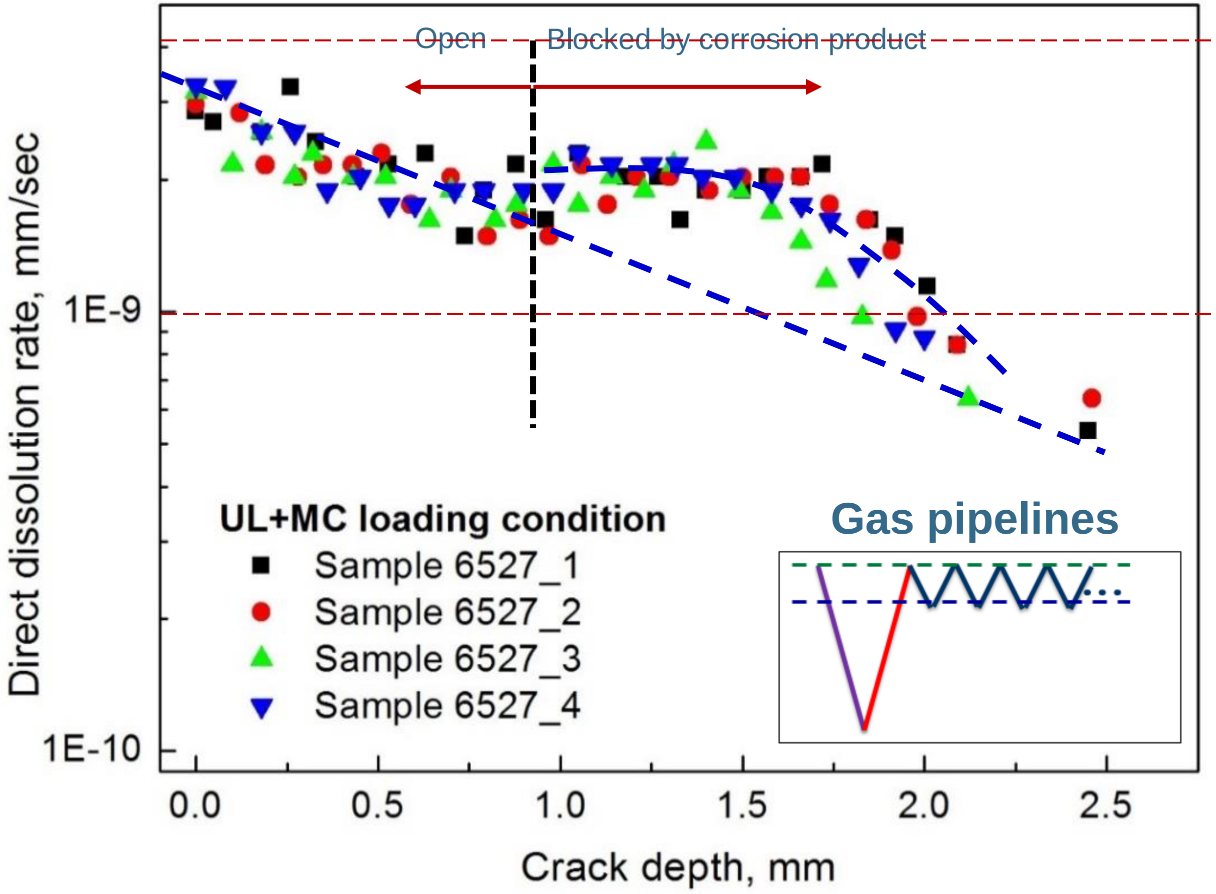
At depth tip

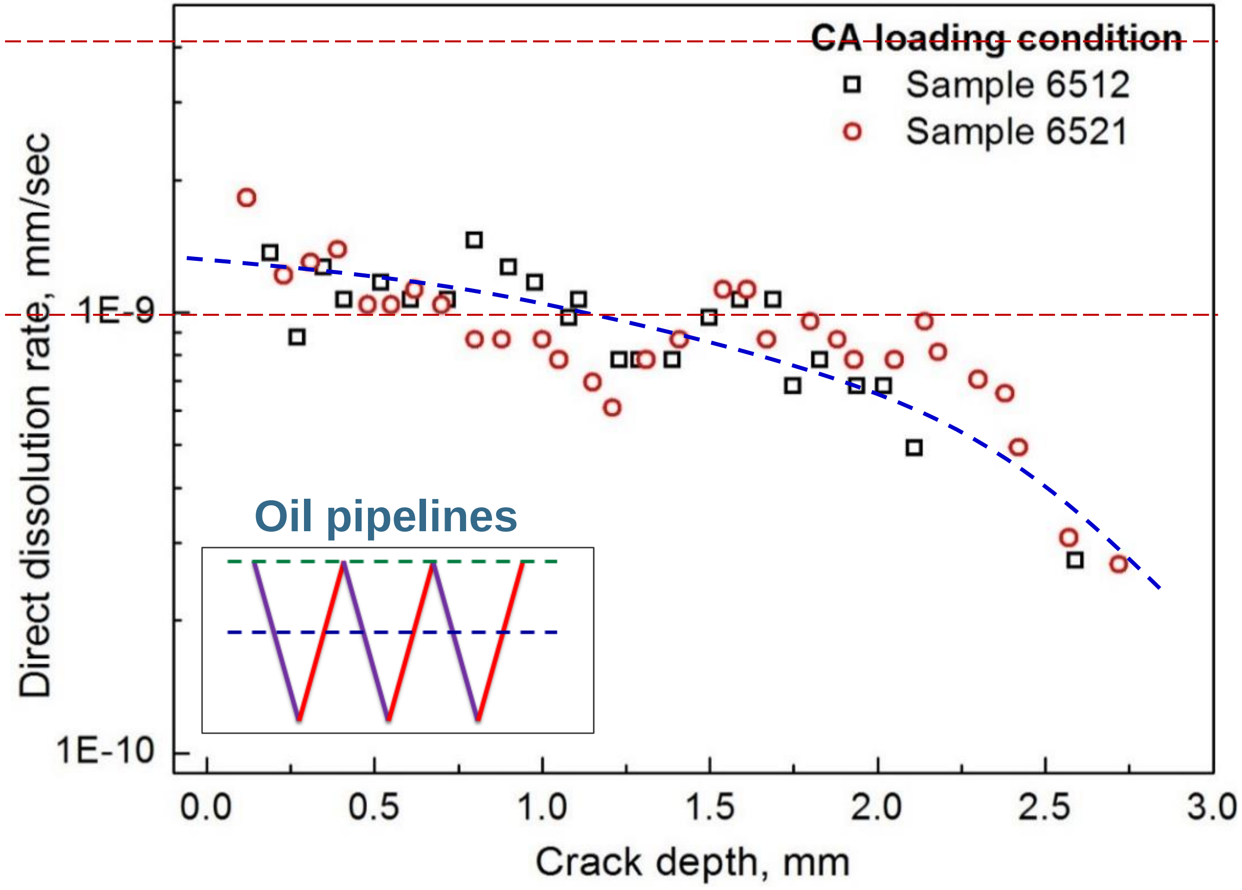


Relationship between crack growth rate on surface tip and direct dissolution rate under various combined factor(fully exposed condition)

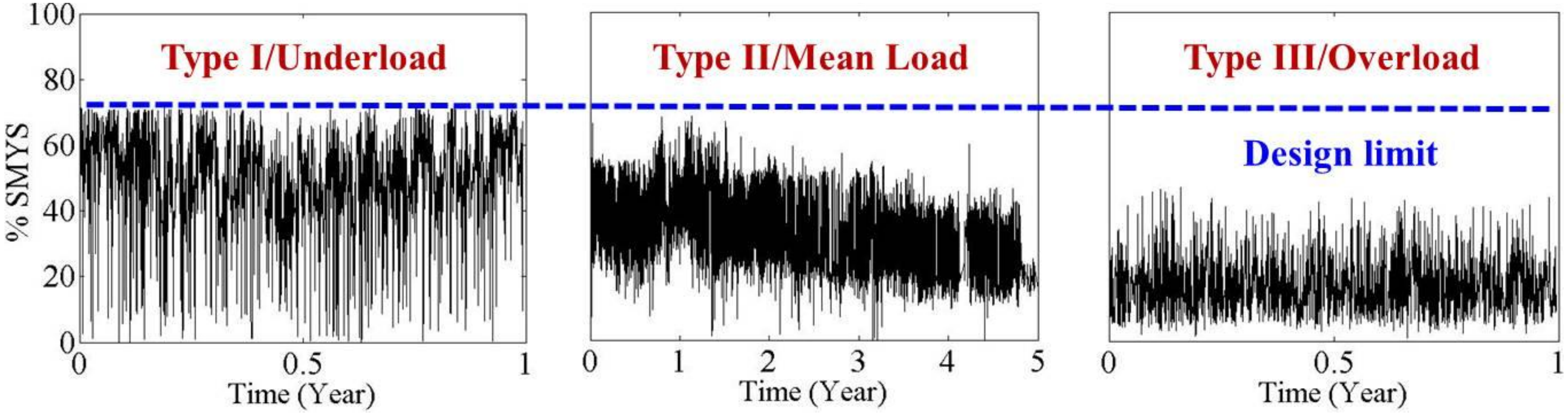
4. Contribution to crack growth by corrosion affected by PFs

At depth tip

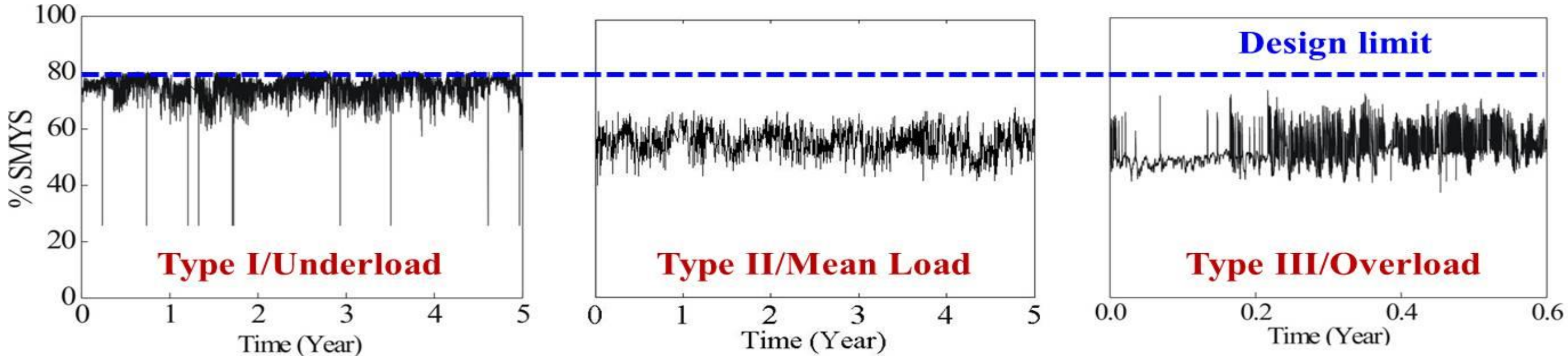




5. Crack Growth under variable amplitude loading



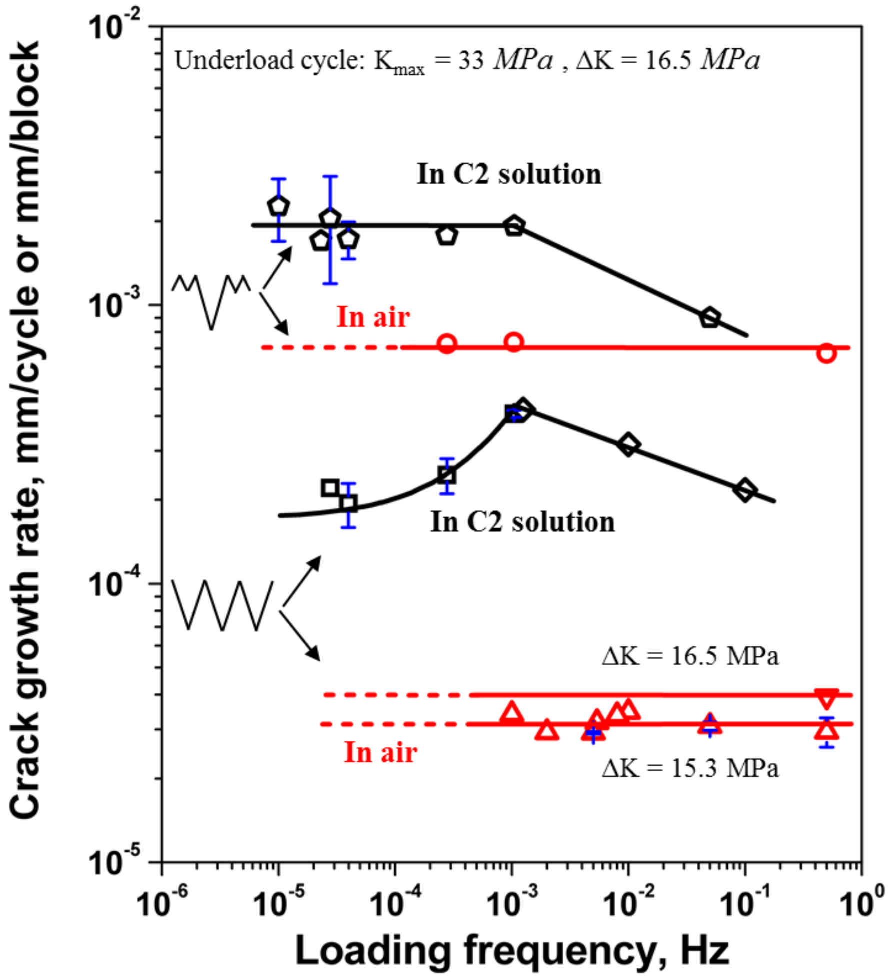
Oil Pipeline

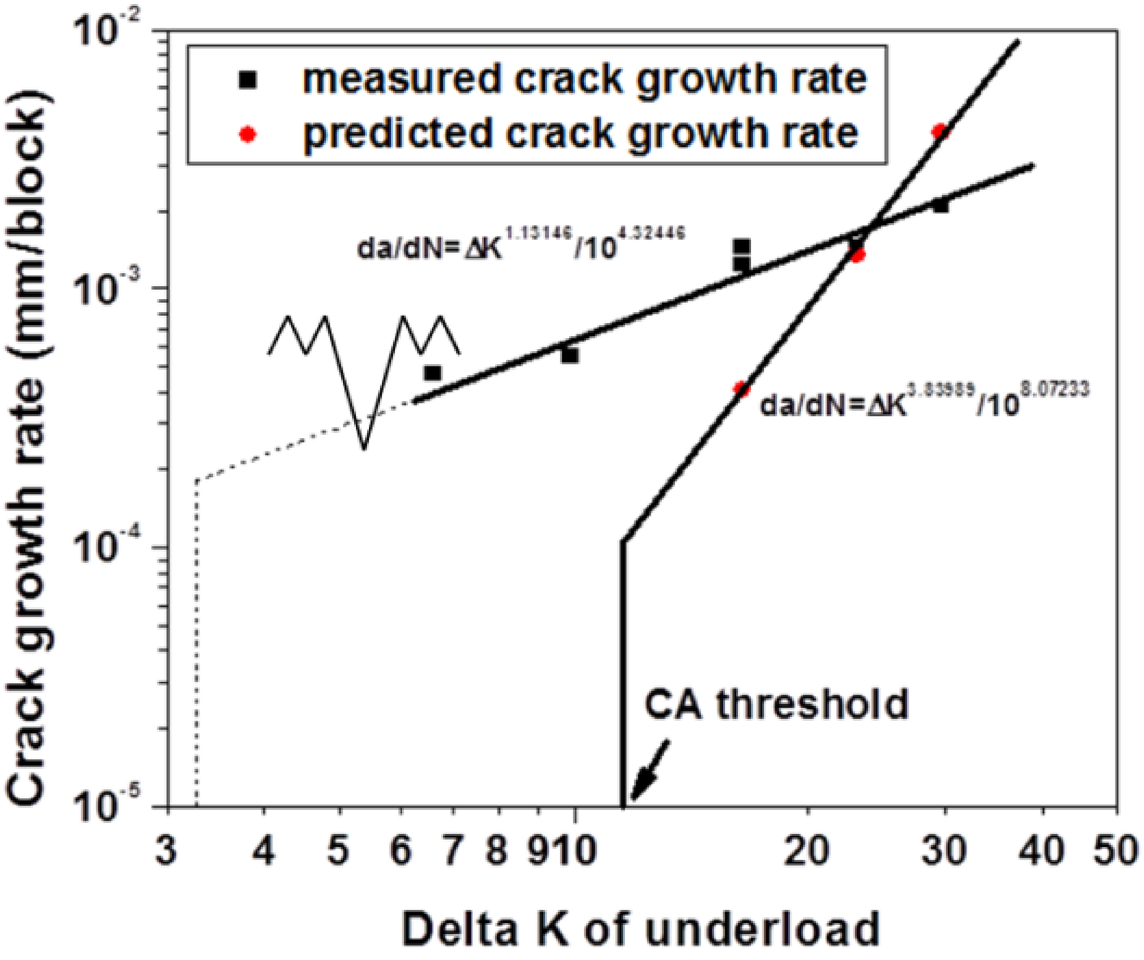


Gas Pipeline

J. Zhao, K. Chevil, M. Yu, J. Been, S. Keane, G. Van Boven, R. Kania, W. Chen, Statistical analysis on underload-type pipeline spectra, Journal of Pipeline Systems - Engineering and Practice, June 28, 2015, under review.

5. Crack Growth under variable amplitude loading





- M.Yu, X. Xing, H. Zhang, J. Zhao, R. Eadie, W. Chen*, J. Been, G. Van Boven, R. Kania, *Acta Materialia*, 96(2015)159-169
- M. Yu, W. Chen, R. Kania, G. Van Boven, J. Been, *International Journal of Fatigue*, Vol 82, January 2016, Pages 658-666.

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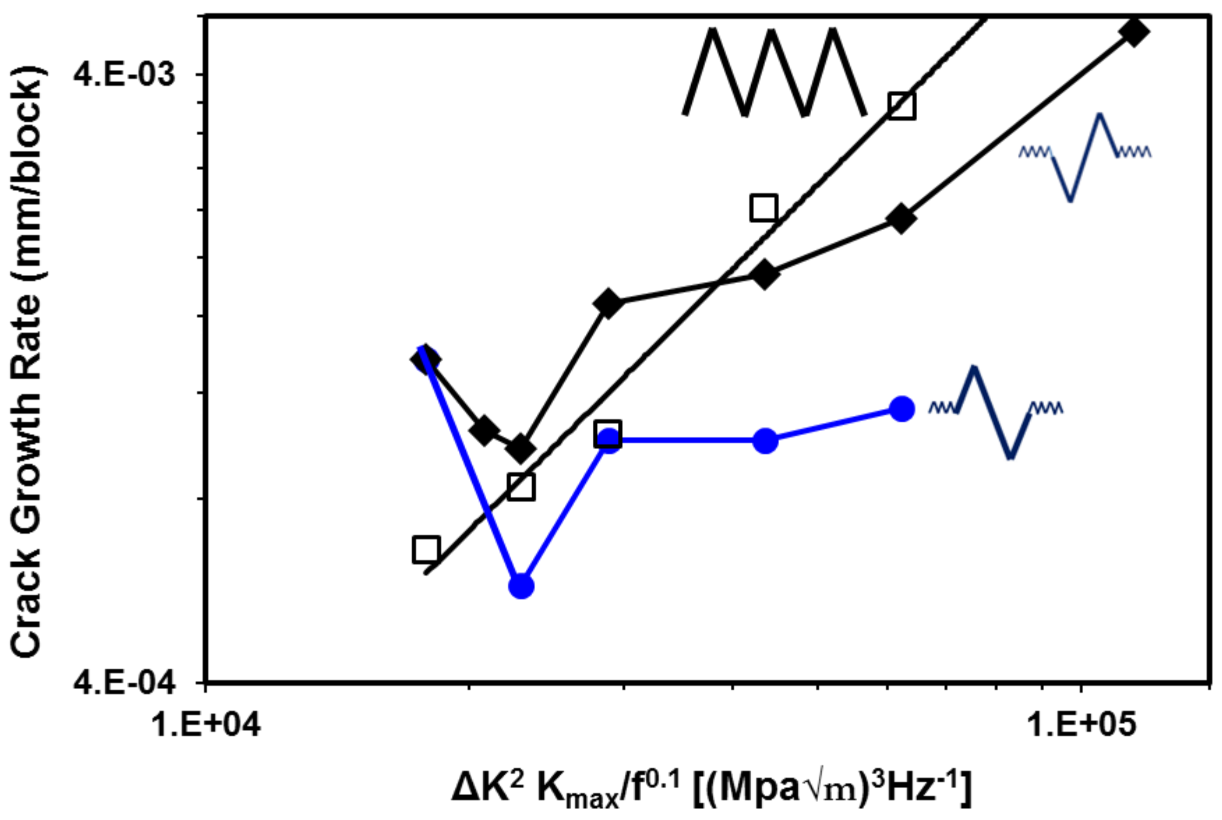
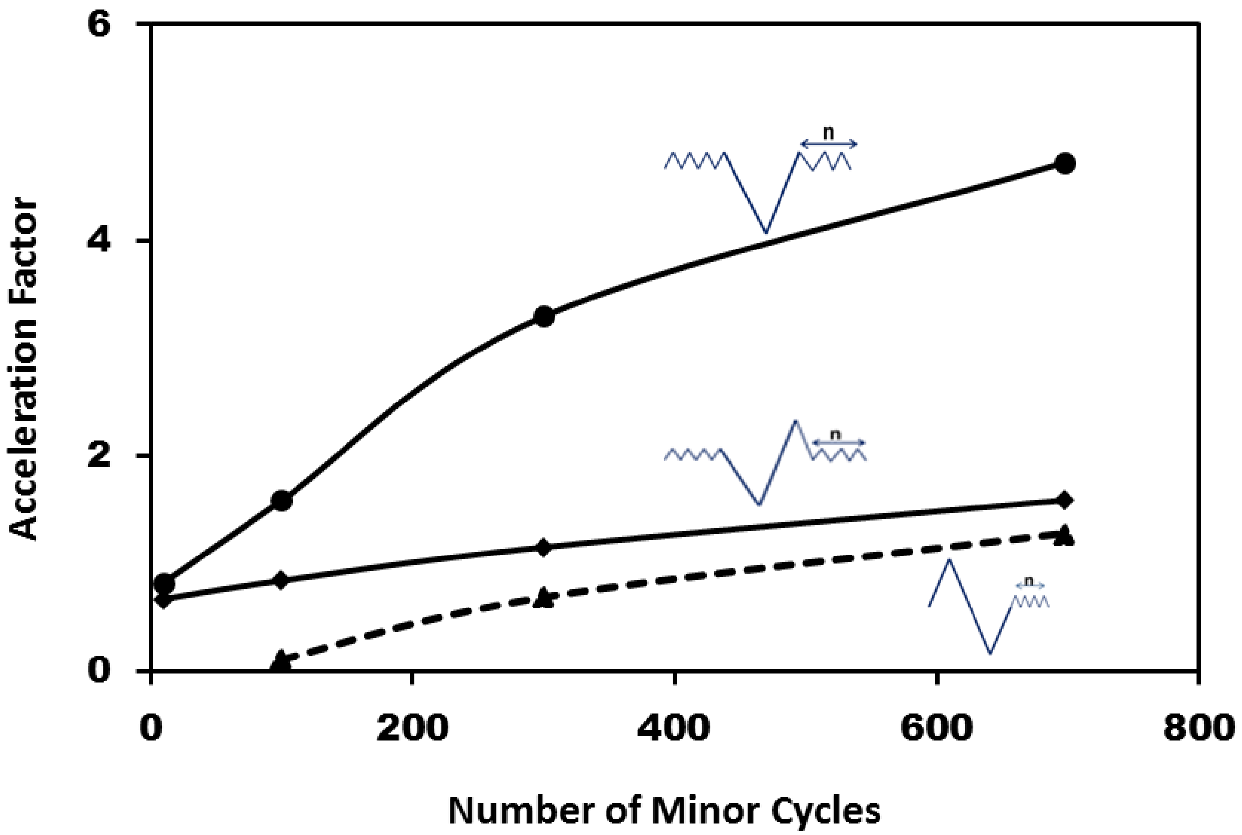


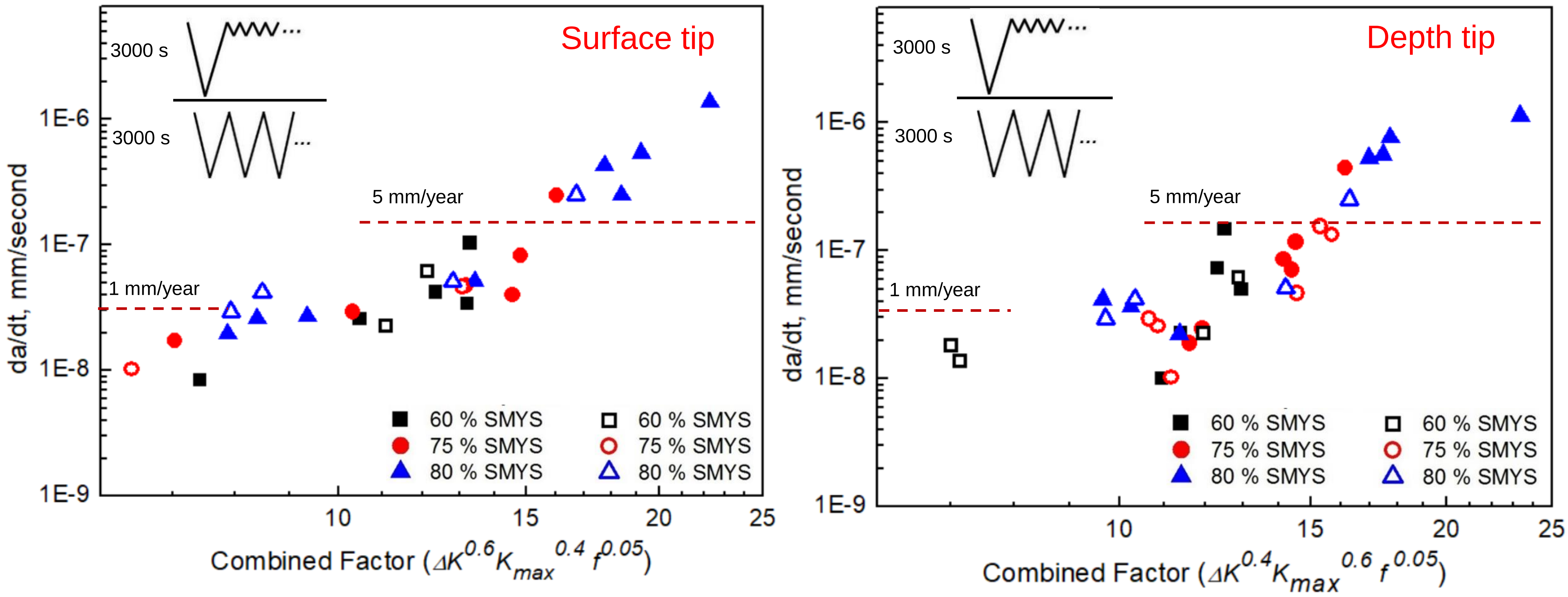


- The underload + overload pressure schemes yielded higher a growth rate than the overload + underload pressure schemes.

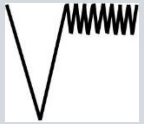
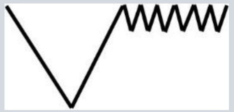
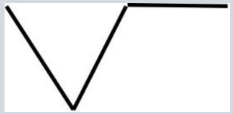
- Overload can reduce the effect of minor cycles on crack growth

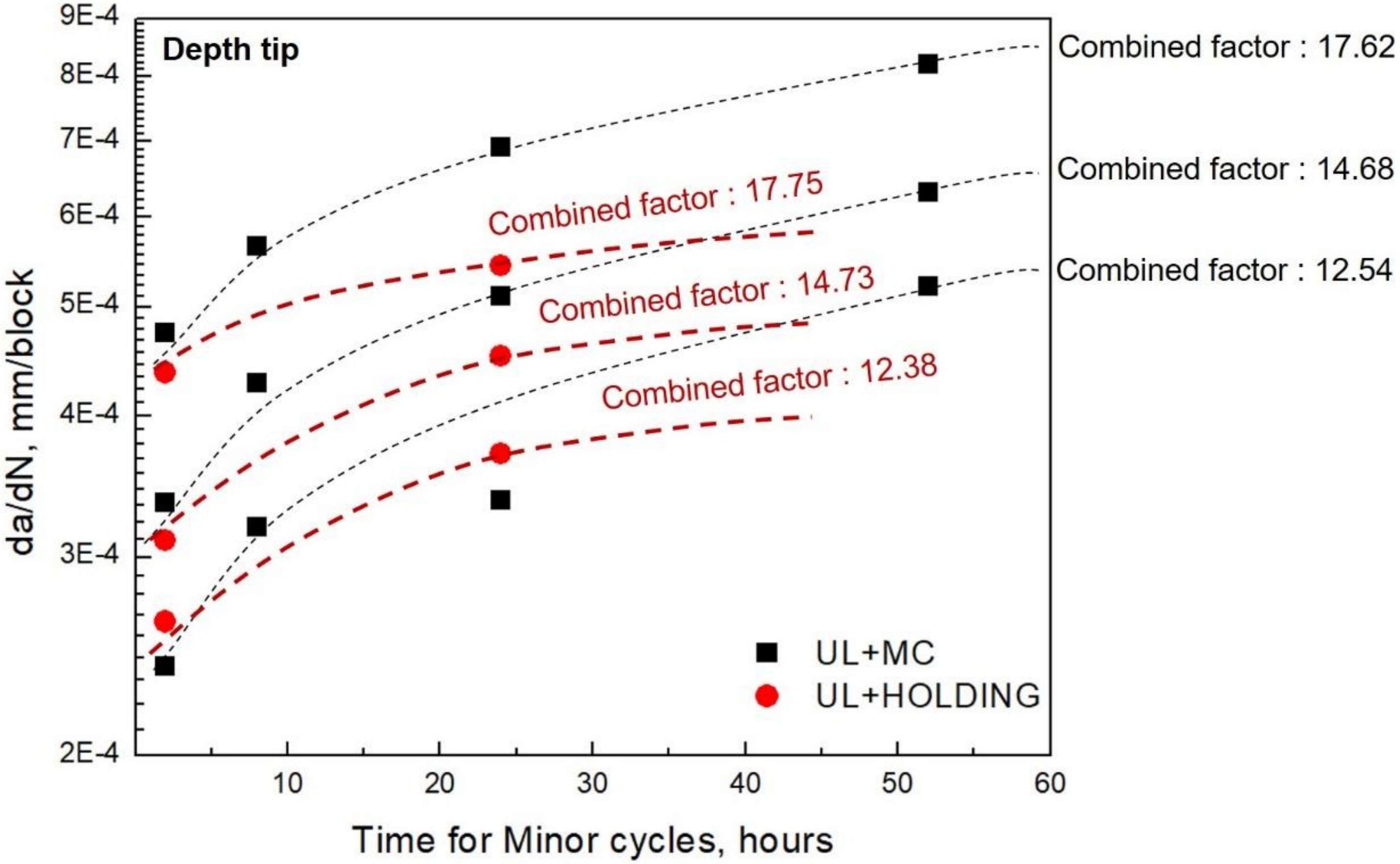
5. Crack Growth under variable amplitude loading

In fully exposed condition

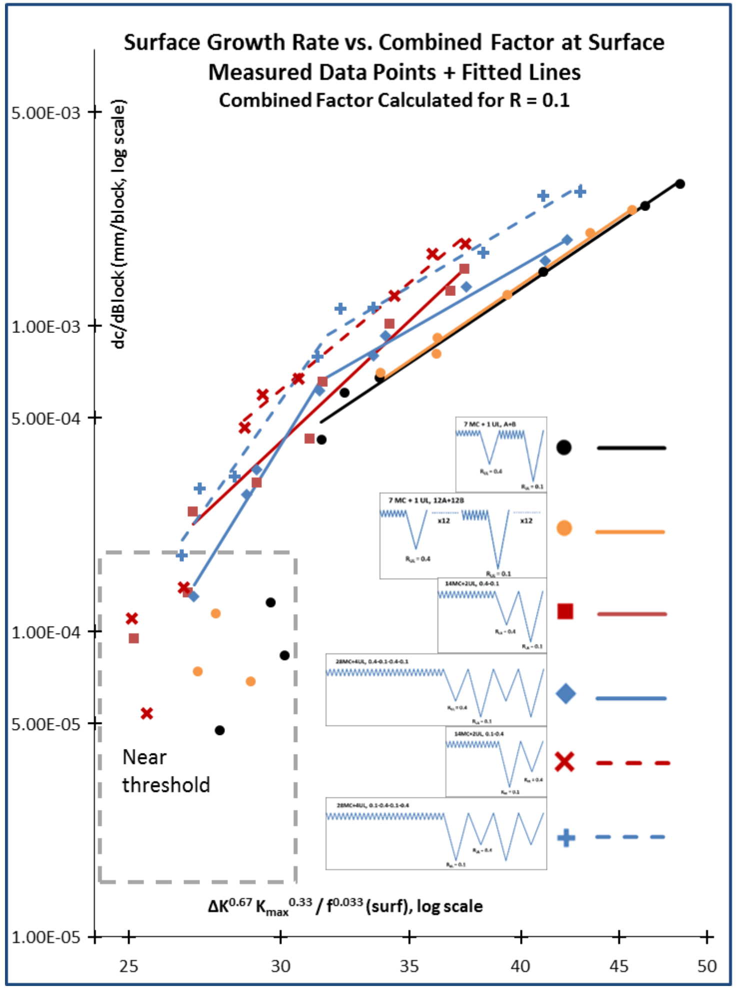


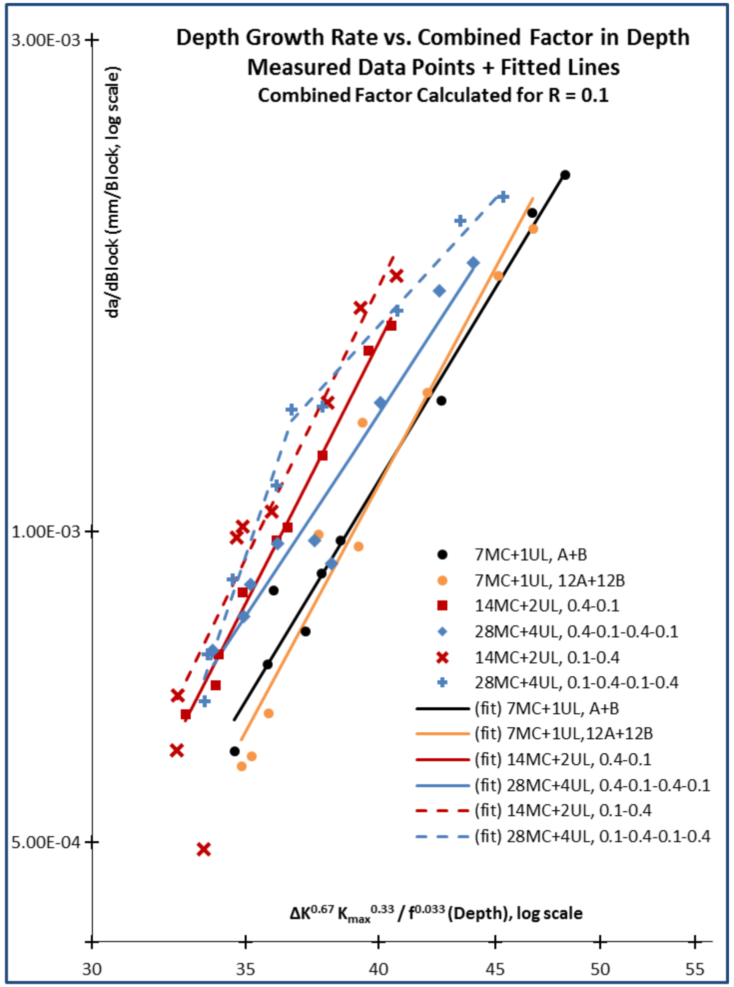
5. Crack Growth under variable amplitude loading

	Oil pipeline	Gas pipeline	
			
$f_{major\ cycle}$	1E-3 Hz	1E-4 Hz	1E-4 Hz
$f_{minor\ cycles}$	5E-2 Hz	5E-4 Hz	-
$R_{major\ cycle}$	0.6 – 0.1	0.5	0.5
$R_{minor\ cycles}$	0.95 – 0.7	0.9	-
Time for minor cycles	0.56 hour	2h, 8h, 24h, 52h	2h, 24h
Maximum stress	60%, 75%, 80% SMYS	80% SMYS	80% SMYS

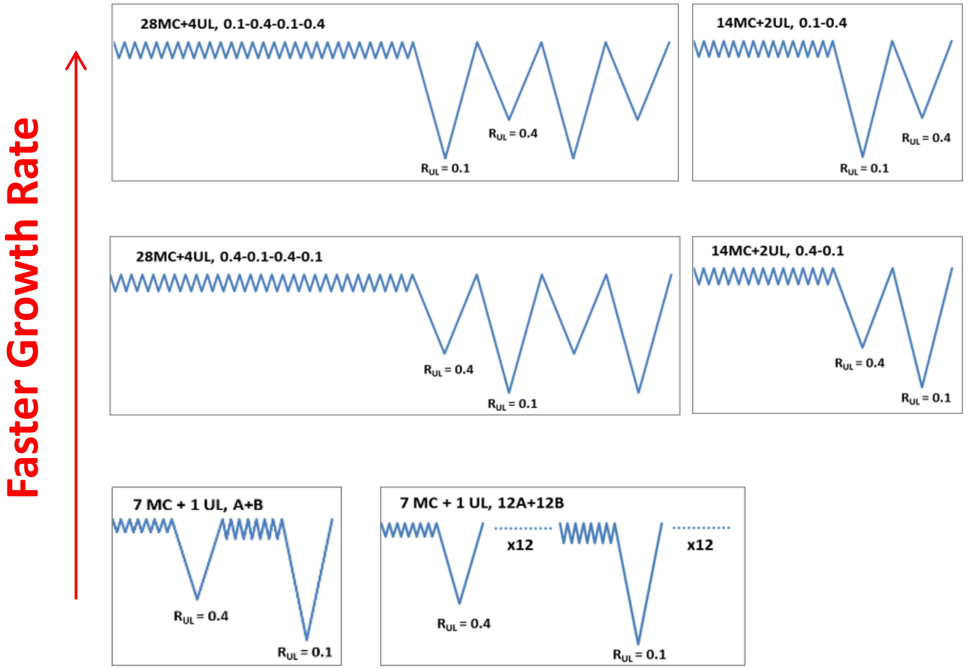


5. Crack Growth under variable amplitude loading





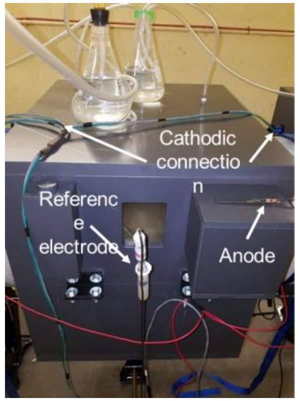
Objective: Does altering the sequence of cycles in an underload spectrum have any effect on crack growth rate?



6. Validation of crack growth models by full scale testing

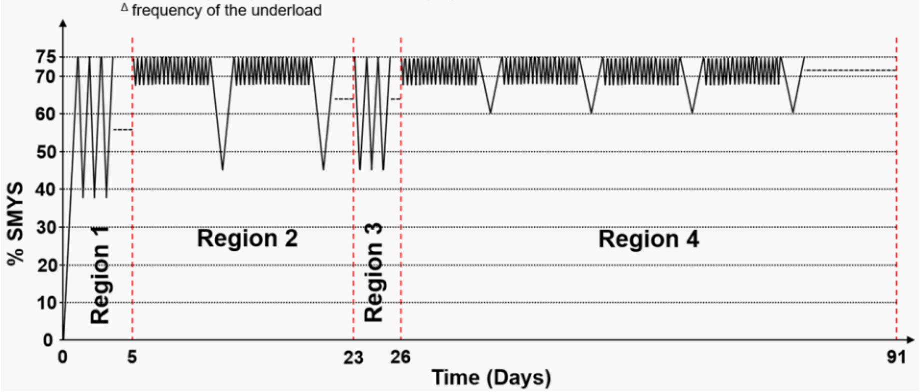
- API X60, NPS 18 spiral welded pipe
- SCH 10, 6.35 mm wall thickness
- Year of construction: 1969
- Removed from service in late 2015
- Multiple crack colonies with largest single crack of about ***2.1 mm deep and 50 mm long***.

- Internal fluid is city water inhibited with 1% CORTRON R-2383
- External boxes hold C2 solution, solution replaced when required
- 5% CO_2, N_2 balance purging through external boxes
- CP: 130 mV below OCP of pipe



Region	Days	Blocks	R UL	R MC*	f^{Δ} (Hz)	Fixed Loading Rate (psi/s)
1	0-5	432	**0.50**	-	0.001	1.25
2	6-23	270	**0.60**	0.90	0.001	1.00
3	24-26	259	**0.60**	-	0.001	1.00
4	27-91	535	**0.80**	0.90	0.001	0.50

* 19 minor cycles (MC) for each underload (UL)
Δ frequency of the underload



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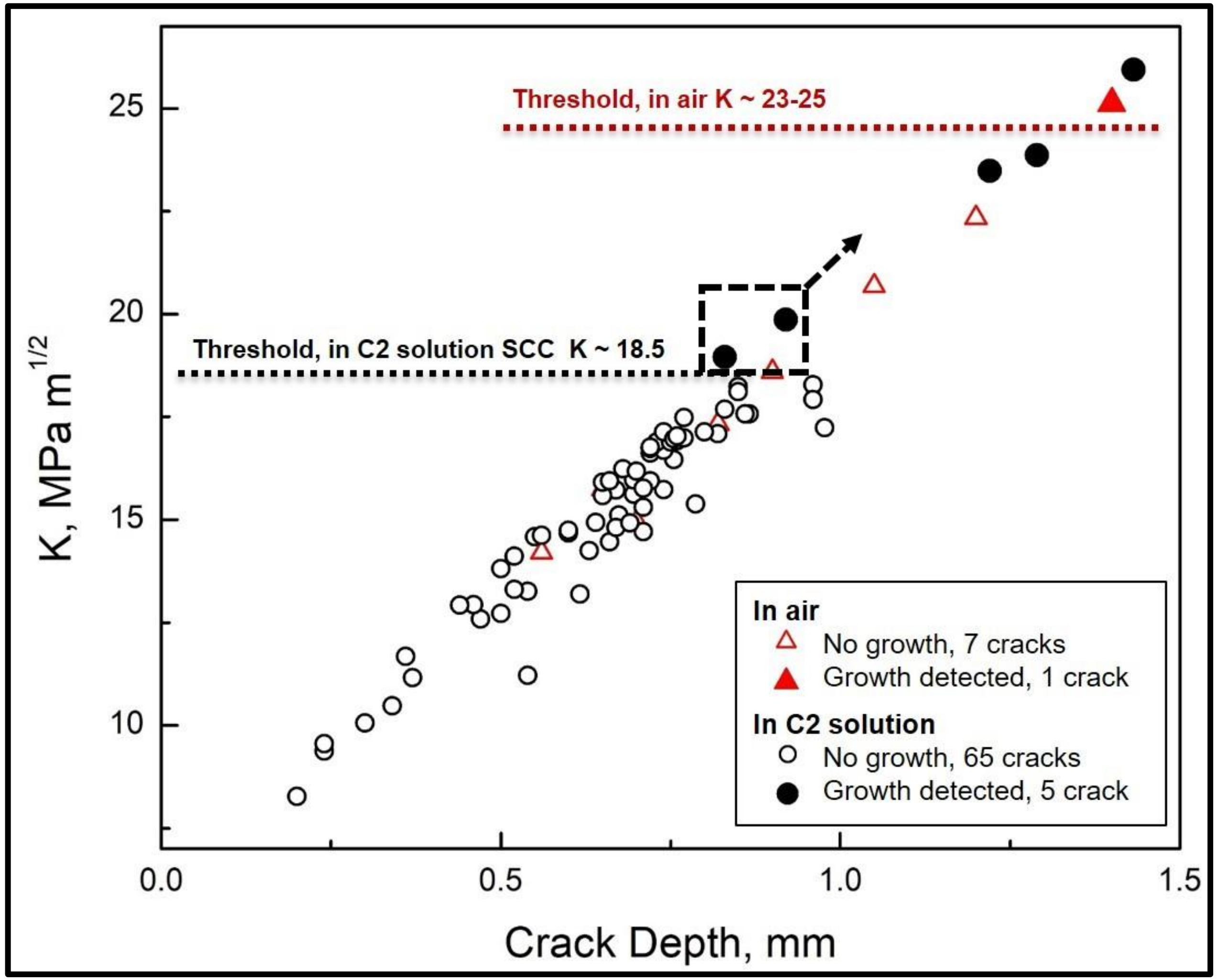
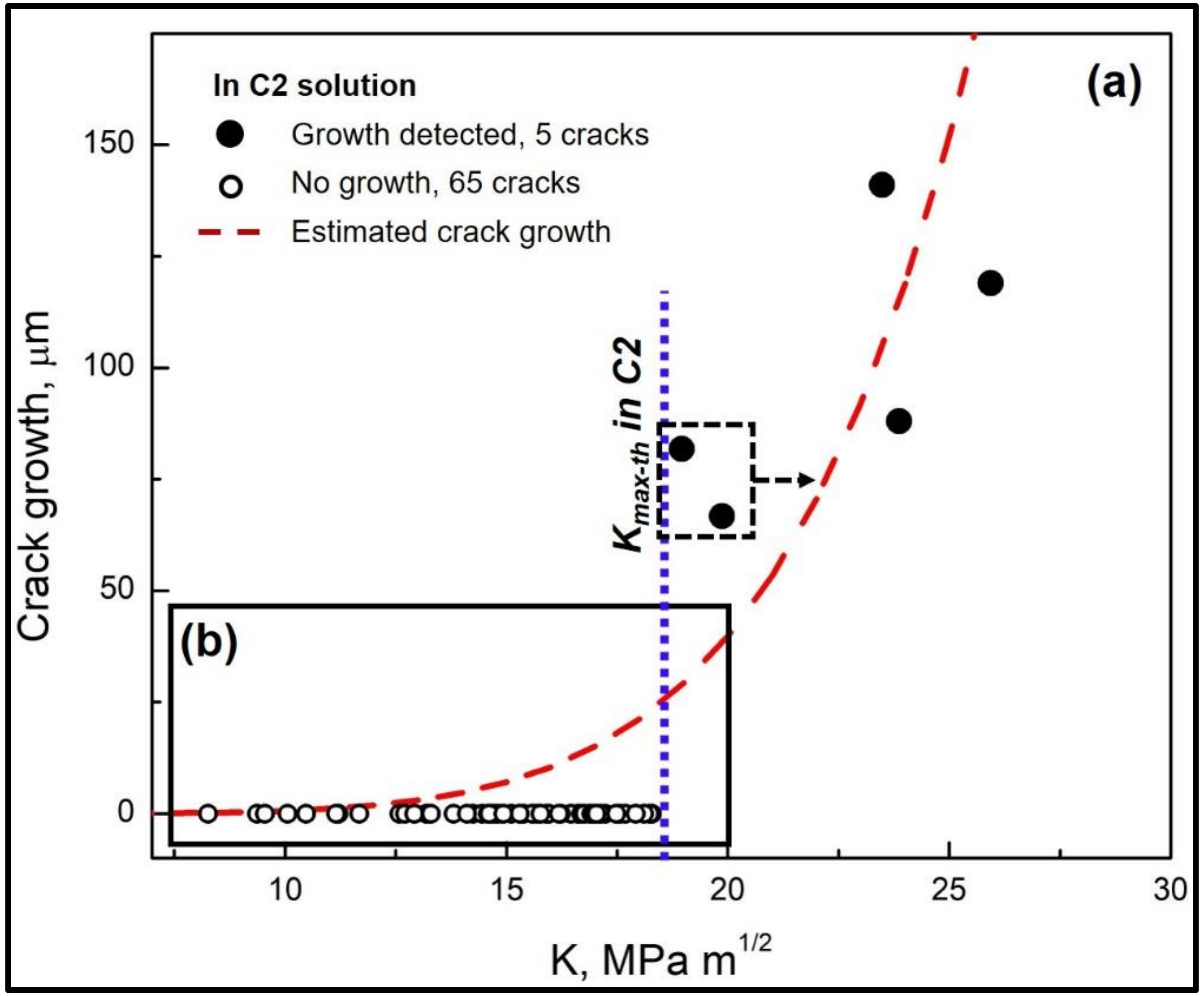




7. Probability of crack growth affected by pressure fluctuations

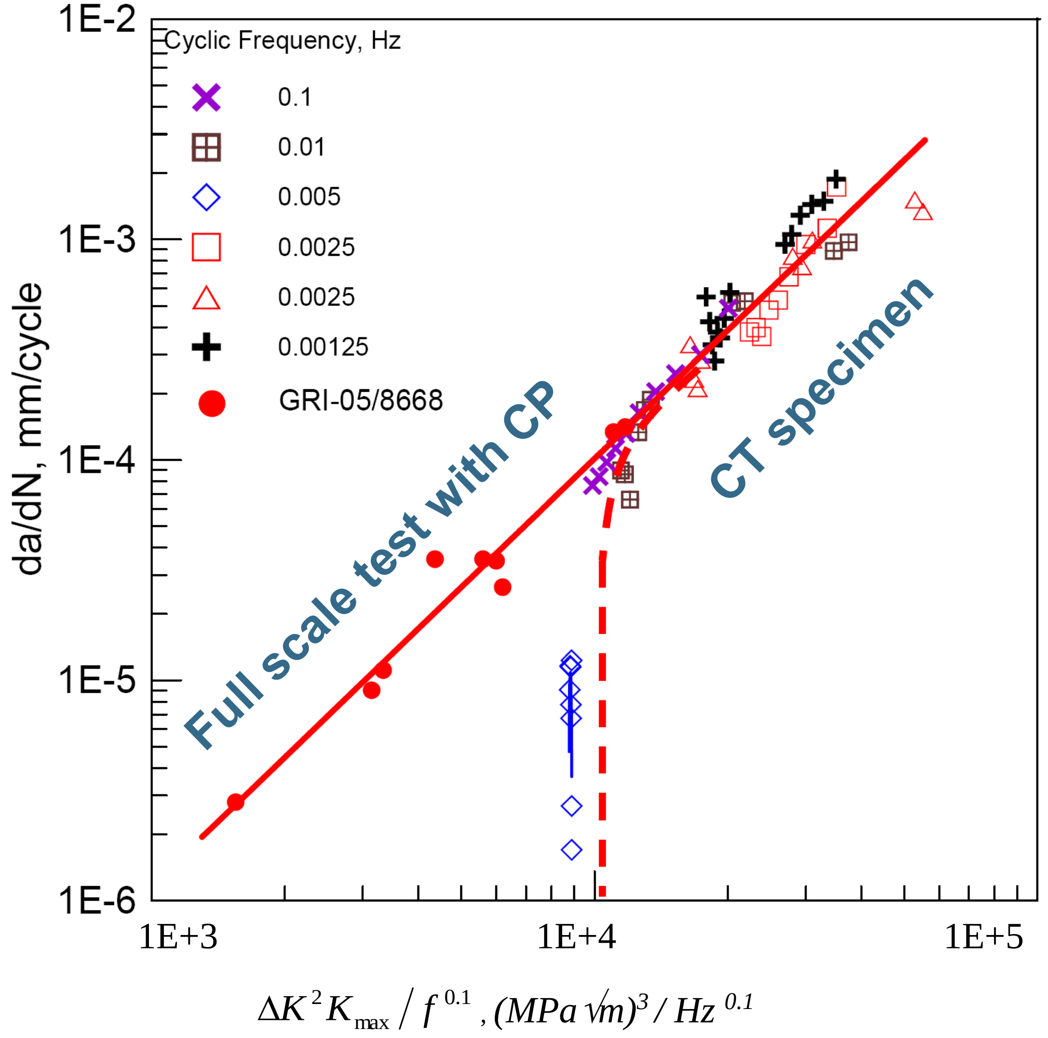
The accuracy of crack growth models can be affected by a number of situations:

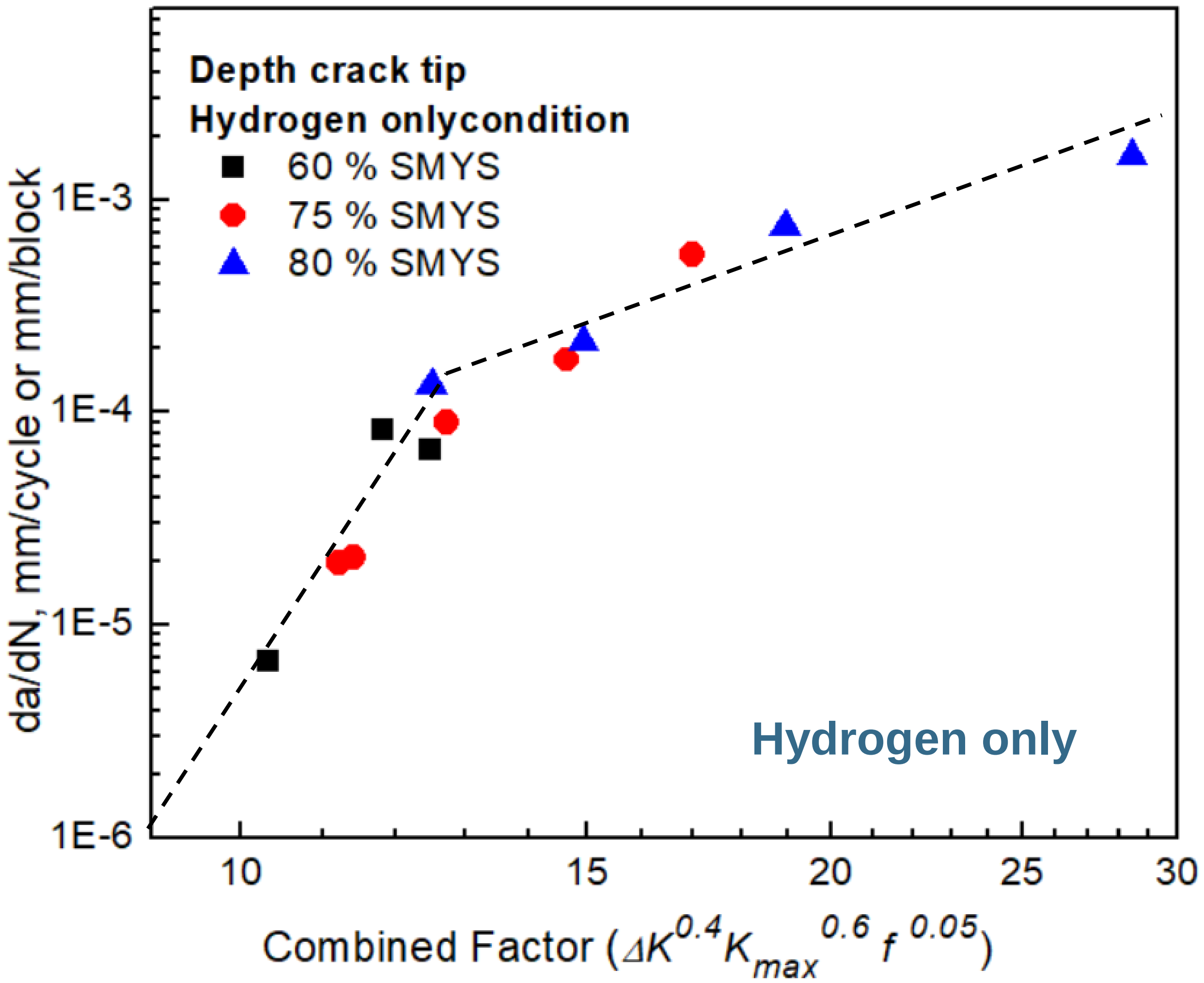
1) Experimental errors: These include the deviation of experimental conditions from the designed values and human errors in crack growth measurements,
2) Difference between laboratory simulations and field conditions when models from laboratory simulations are applied to predict growth behavior of pipeline steels under field conditions.
3) Uncertainties of field conditions: Laboratory simulations are conducted under relatively consistent conditions, while seasonal changes in environments and random pressure fluctuations are encountered during field operation.

The largest errors of prediction are caused by the so-called “growth” and “no-growth” threshold situations:

1) At very low crack growth rate under which the time available for corrosion dissolution at the crack tip become appreciable, and low temperature creep, especially hydrogen facilitated plastic deformation, could also occur and blunt the crack tip.
2) When cathodic protection is not available or insufficient, corrosion caused crack tip blunting is possible
3) Overloading, such as during hydrostatic testing, or pressure surge, especially when crack depth is large.
4) When the crack is deep, and the bulk concentration of diffusible hydrogen surrounding the crack tip is low because of concentration gradient of diffusion (highest at the steel surface where the hydrogen is generated).

7. Probability of crack growth affected by PFs

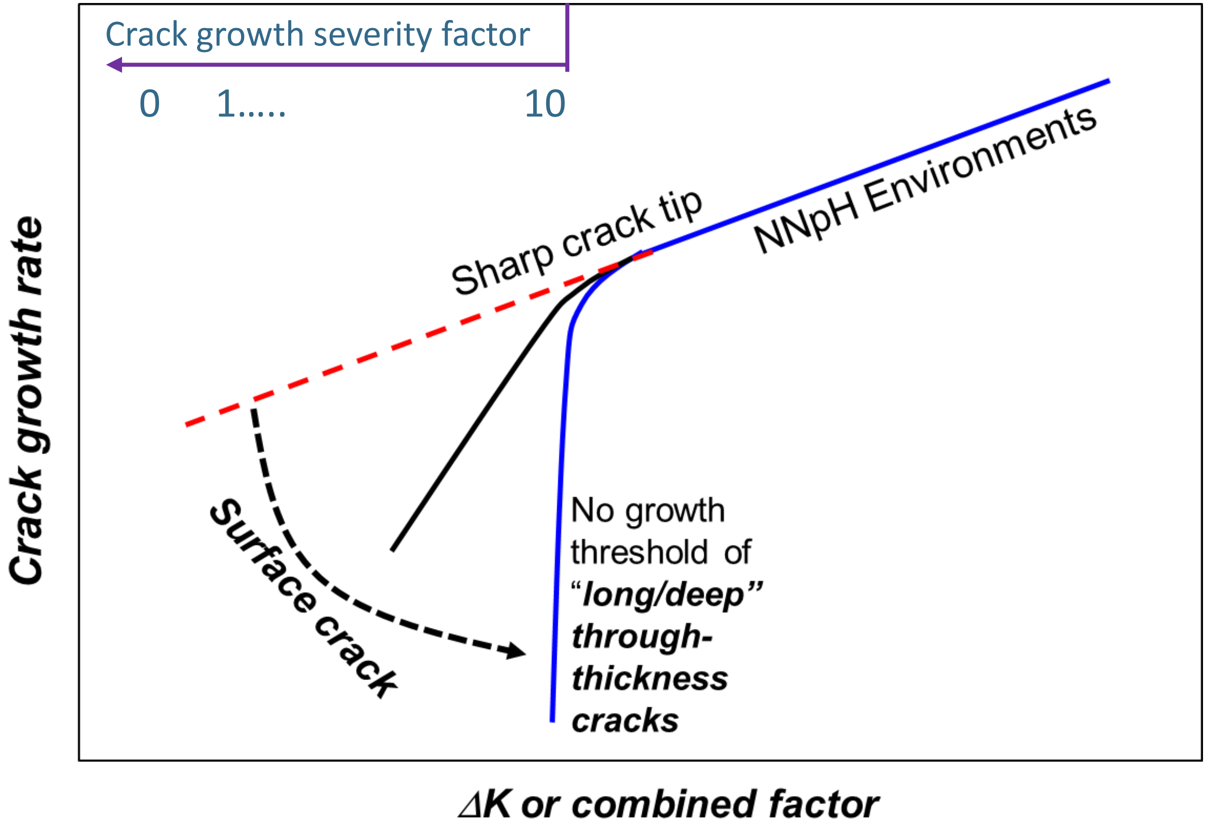




W. Chen, R. Kania, R. Worthingham and S. Kariyawasam, â€œCrack growth model of pipeline steels in near neutral pH soil environmentsâ€•, Proc. of the 7th International Pipeline Conf., IPC2008, Sep 29 â€“ Oct 3, 2008, Calgary, Canada, Paper # IPC2008-64475, 10 pages.

7. Probability of crack growth affected by PFs

Crack growth at the depth tip of a surface crack

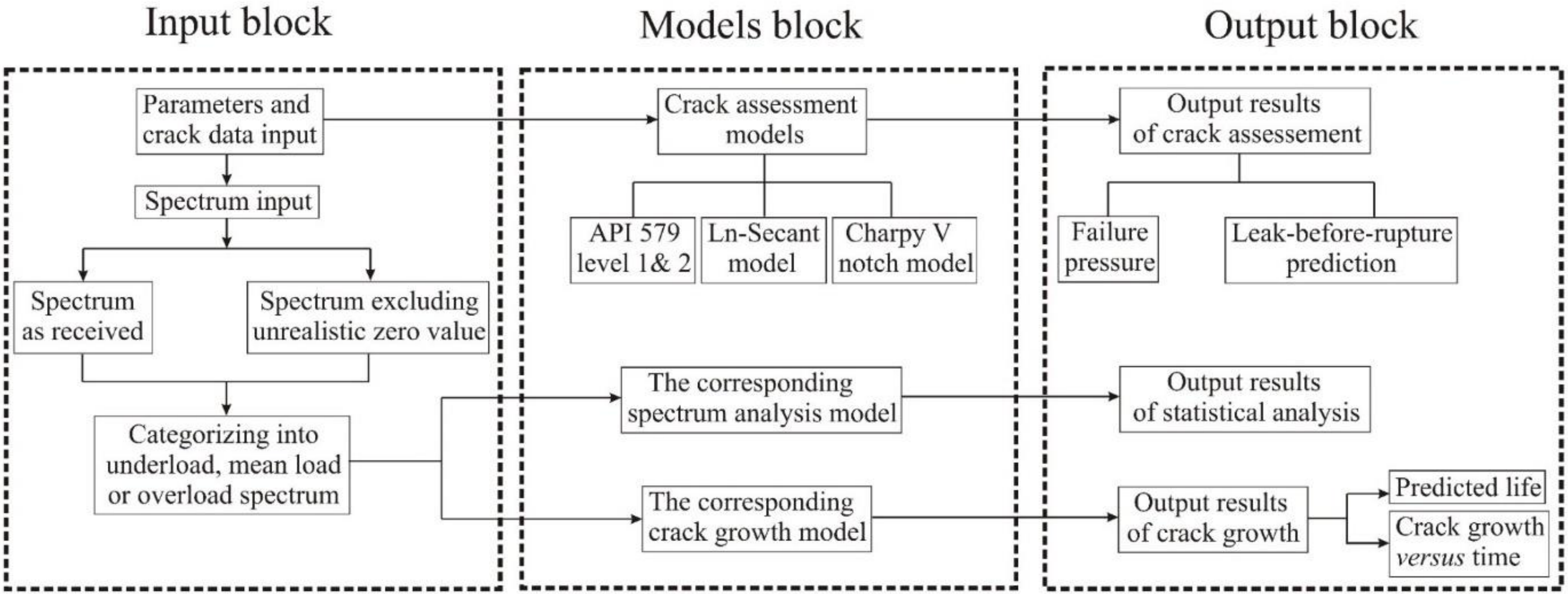


Crack growth severity factor	Description
0	This is the most severe case of crack growth without setting a threshold for the combined factor [corresponding to a situation at which crack tip remains sharp even under low combined factor (free of crack tip blunting by corrosion].
1 to 9	It represents various crack growth situations between the most severe (crack growth severity factor = 0) and the least severe (crack growth severity factor = 10) case of crack growth.
10	This is the least severe case of crack growth with a highest threshold value for the combined factor possible (corresponding the threshold determined from using compact tension specimens).

9. Pressure optimization to reduce the risk of NNpH SCC failure

Category	Describtions
Common working principle	• By the concept of crack growth retardation effect or the so-called overloading effect, which is achieved by temporarily increasing the operation pressure higher than the maximum operating recorded over a period before the temporary increase of operation pressure. • Crack tip blunting induced by low temperature creep and plastic deformation • Crack tip blunting caused by excessive corrosion at the crack tip, especially when pipelines are not pressurized. • A combination of 1) to 3) achieved with minimum crack growth during the process overloading and with reduced crack growth after the process of overloading.
Working principle specific of near-neutral pH solutions	• Blunting crack tip by corrosion prior to or after overloading. • A hydrotest or overloading scheme that could cause minimum H trapping during pressurization and maximum H effusion during depressurization. • Perform hydrotest or overloading at higher temperatures, e.g., over 60^{o}C, to minimize the effect of H-embrittlement.
Working principle specific of operating conditions	• Develop a cathodic potential strategy combined with seasonal ground water conditions and operation pressure to achieve crack tip blunting. • Develop pressure operating schemes that are specific to the pressure fluctuation-types, that is, underload, mean load or overload. • Develop an operating strategy for pipe sections with high operation pressure, and frequent and high amplitude underload cycles to prevent crack tip from re-sharpening.
Working principle specific of cracking stages	• For pipeline sections with crack dimensions in the stage of crack initiation and early-stage of growth (Stage 1), efforts should be made to achieve crack tip dormancy at the surface tip of a crack to prevent crack length extension. • For pipeline sections with crack dimensions that are subject to crack growth under mechanical driving forces higher than the threshold (Stage 2), attention should be focused on achieving crack tip dormancy/blunting at the depth tip of a crack. To achieve Stage 1 crack dormancy: • Cathodic protection should be sufficient to avoid the occurrence of corrosion on the surface of pipeline steel. • Pipeline operation should be performed to avoid the occurrence of underload cycles. To achieve Stage 2 crack dormancy: • Pipeline operation should be performed to avoid the occurrence of underload cycles. • Decrease the MAOP to reduce the % of SMYS. • Perform hydrostatic testing and or an overloading event with a stress higher than the upper point of yield. • A free corrosion condition is achieved to allow crack tip blunting by corrosion before, during and after hydrostatic testing or an event of overloading before resuming regular operation. • A seasonal condition that allows the increased corrosion at the crack tip, especially under zero pressure, for example, right before and/or after a hydrostatic testing for a controlled time before resuming regular operation.

8. PipeOnline software for CGR/remaining life assessments



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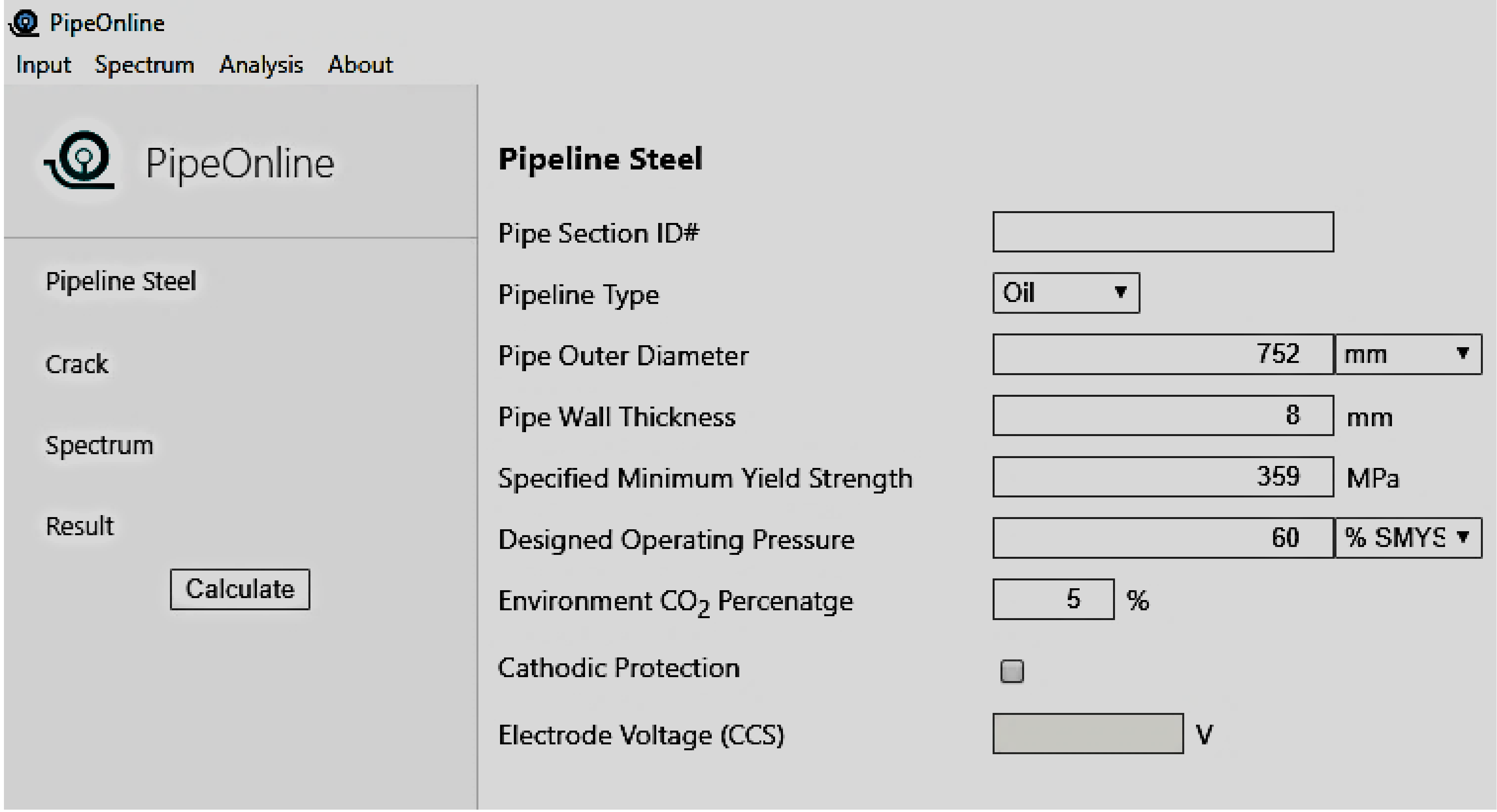

10. Summary and conclusions

1) Near neutral pH crack initiation is pressure fluctuation dependent. Severe pressure fluctuations accelerate the fracture and spallation of mill scale on the pipeline steel surfaces, making it harder to initiate SCC cracks from the bottom of pits that tend to develop at flawed mill scale sites. On the other, the presence of the primer layer before applying the protective coating preserves the mill scale on the pipe steel surface and promotes crack initiation.
2) The early-stage crack growth primarily occurs by crack length extension along the pipe surface but limited crack growth in the depth direction. Three different mechanisms of crack length extension have been identified, including determination by coating disbondment, stochastic process of crack coalescence, and crack initiation and growth induced by the existing cracks. The latter process is pressure fluctuation sensitive.
3) A complete set of equations governing crack growth in Stage 2 has been established using specimens with surface cracks under mechanical loading conditions that were similar to pressure fluctuations that had been measured during the operation of oil and gas pipelines.
4) The contribution to crack growth by direct dissolution of iron at the crack tip has been determined, which has been found to be crack depth-dependent and pressure fluctuation-sensitive. Gas pipelines operated under high mean pressures show higher rates of dissolution.
5) The severity of crack growth and the accuracy of the predictive model can be significantly affected by crack tip morphology, either sharp or blunt, and this would yield different threshold values for the onset of Stage 2 crack growth and therefore different estimates of remaining life.
6) The PipeOnline software has been revised to incorporate the new experimental results obtained from the current PRCI project. This PipeOnline software was previously developed from the two earlier phases of the PRCI project.
7) Based on the understanding of cracking mechanisms, strategies, and models of achieving crack dormancy and prevention of crack from growth have been proposed.

Acknowledgements

- **Pipeline Research Council International (PRCI)**: PRCI SCC 2-12A team
- **Enbridge:** *Lyndon Lamborn, Stephen Wood, Dr. Colin Scott, Sean Keane*
- **TC Energy**: *Karina Chevil, Dr. Jenny Been (now with NEB), Richard Kania, Bob Sutherby, Bob Worthingham, Dr. Shahani Kariyawasam*
- **Spectra Energy:** *Greg Van Boven (was also with Enbridge Pipelines, now with* North River Midstream Inc.)
- **DOT PHMSA**
- **Natural Sciences and Engineering Council of Canada (NSERC)**
- **University of Alberta**:
  - Graduate students/PDF for many years: Dr. Zhezhu Xu, Dr. Shidong wang, Greg Nelson, Dr. Jiaxi Zhao, Mengshan Yu, Karina Chevil, Xing Xiao, Devin Engel, Brett Conrad, Abdoulmajid Eslami, Afolabi Egbewande, Dr. Yongwan Kang, Mohammad Marvasti, Greg Van Boven…...
  - Colleagues: Dr. Hao Zhang and Dr. Reg Eadie

Thank you for your attention.