

# SSC Performance of TMCP-based Large-Diameter Pipes in High H<sub>2</sub>S Partial Pressure Environments

Christoph Bosch, EUROPIPE

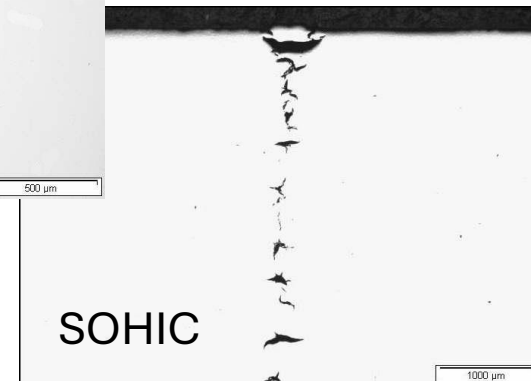
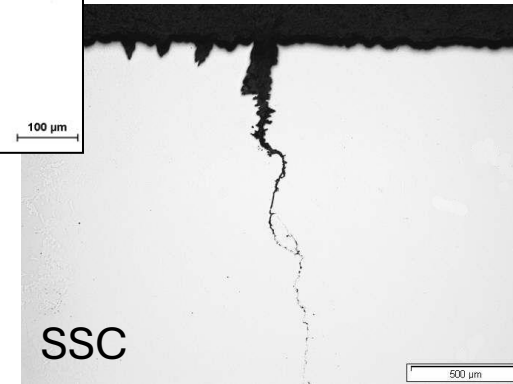
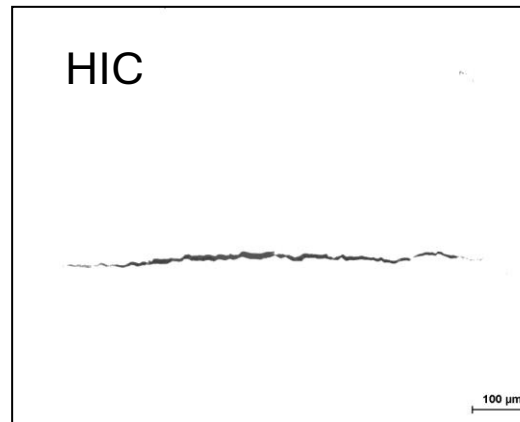
Thomas Haase, Salzgitter Mannesmann Forschung



# Introduction

## Line pipe steel for sour service environments

- Oil or gas containing aqueous Hydrogen Sulfide ( $\text{H}_2\text{S}$ )
- Corrosion reactions of steel with  $\text{H}_2\text{S}$ 
  - Formation of atomic hydrogen
  - Hydrogen uptake and diffusion
  - Prerequisite for crack initiation
- Different forms of cracking in steel
  - HIC (Hydrogen Induced Cracking)
  - SSC (Sulfide Stress Cracking)
  - SOHIC (Stress-Oriented Hydrogen Induced Cracking)
- Resistance testing as qualification for sour service suitability



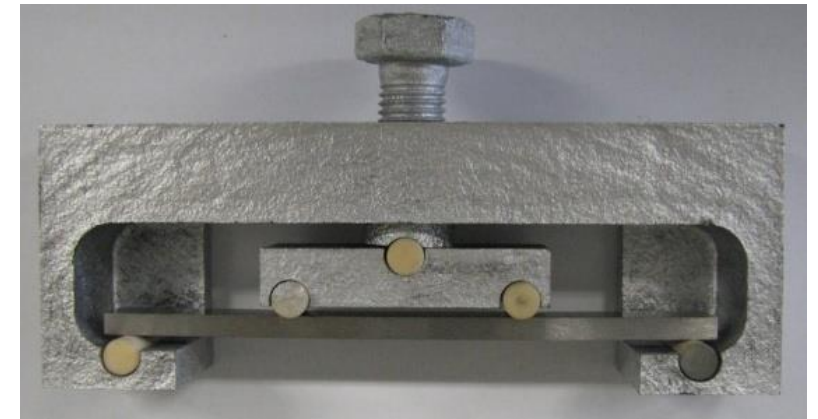
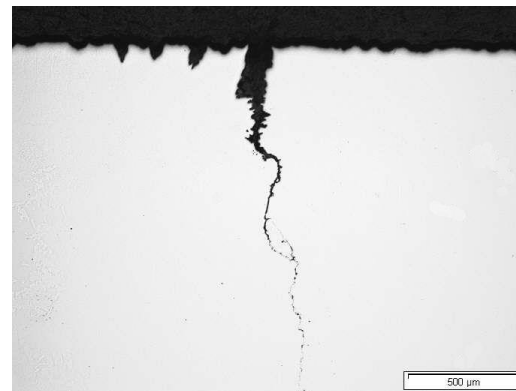
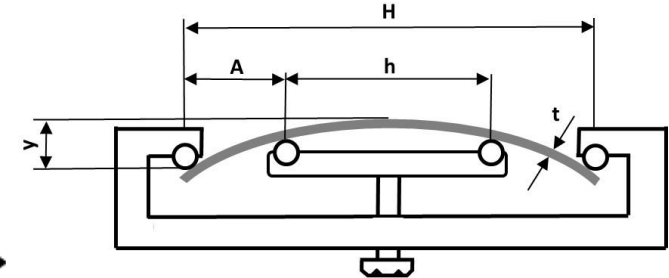
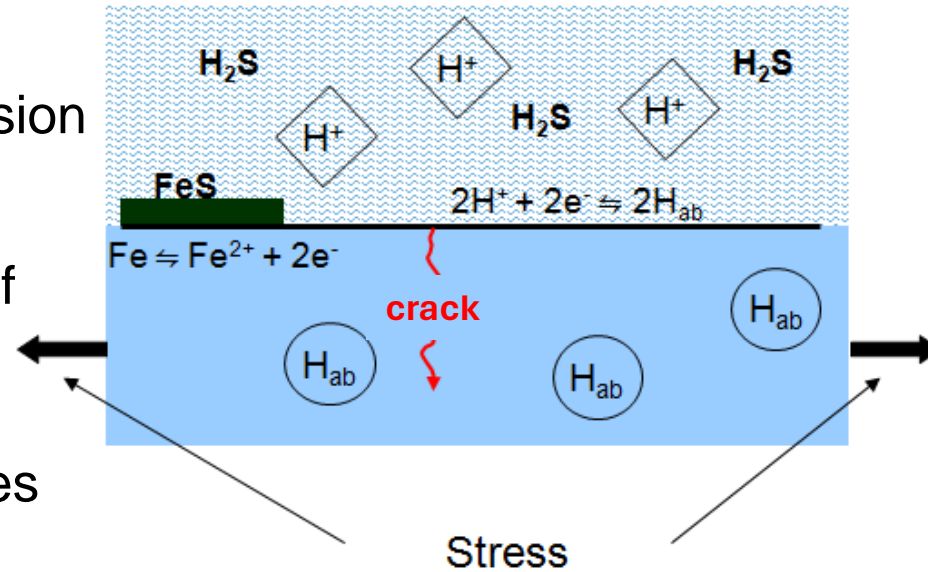
# Sour Service – SSC Testing

## Sulfide Stress Cracking

- Atomic hydrogen from  $\text{H}_2\text{S}$  corrosion
- Hydrogen uptake and diffusion
- Cracking from combined action of
  - Hydrogen embrittlement
  - External or residual stresses

## SSC testing

- Mandatory qualification test
- Four-point bend test
  - EFC Publ. No. 16
  - NACE TM0177-2016
  - **NACE TM0316-2023**

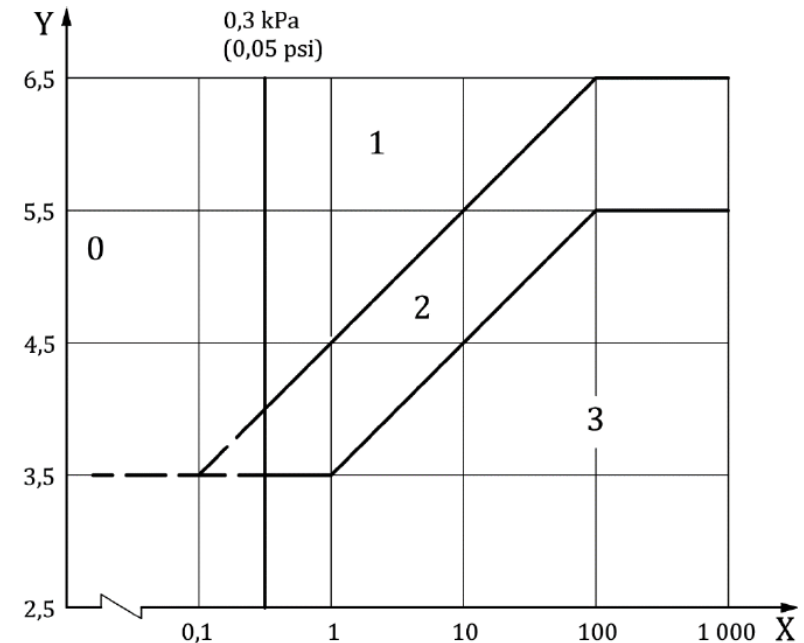


# SSC Test Requirements

## Qualification according to NACE MR0175 / ISO 15156-2

- Environmental severity based on  $p(\text{H}_2\text{S})$  and pH
- Concerns about validity of region 3 for  $p(\text{H}_2\text{S}) > 100 \text{ kPa}$
- Influence of  $\text{CO}_2$ ?

|                             |                  |                |   |  |   |   |
|-----------------------------|------------------|----------------|---|--|---|---|
| All SSC regions of Figure 1 | FPB <sup>j</sup> | ≥80 % AYS      | NACE TM0177 Environment A (5 % mass fraction NaCl + 0,5 % mass fraction CH <sub>3</sub> COOH) | 100 kPa (15 psi) in accordance with NACE TM017 7 | No SSC cracks in accordance with NACE TM0316 assessment method  | —   |
|                             | UT or CR         | ≥80 % AYS      |   |  | No SSC cracks in accordance with NACE TM0177 assessment method  |   |
|                             | DCB <sup>h</sup> | Not applicable |   |  | Assessment shall be in accordance with NACE TM0177. Acceptance criteria shall be by documented agreement <sup>k</sup> | Use as qualification at equipment user's discretion and with documented justification |



### Key

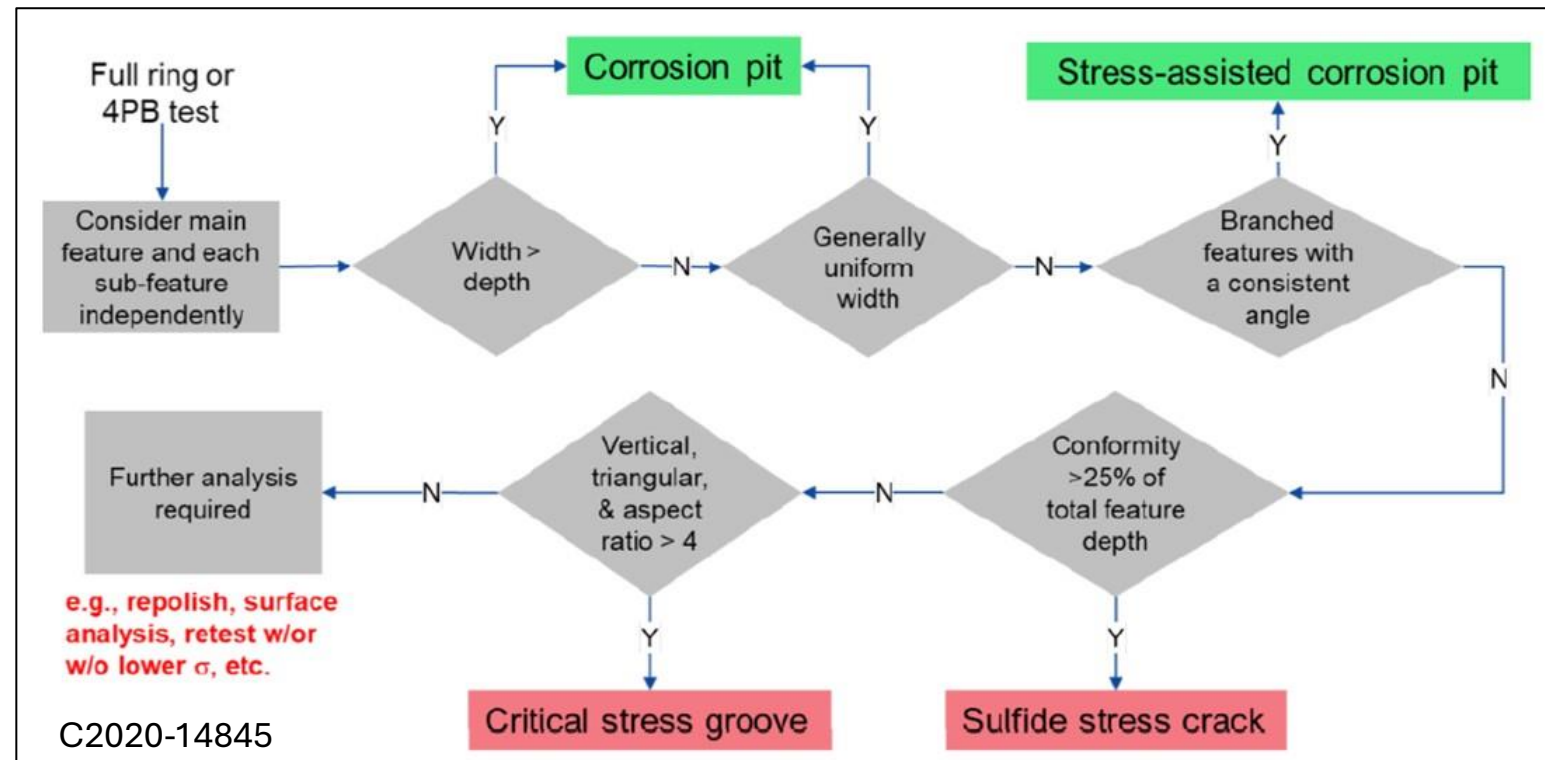
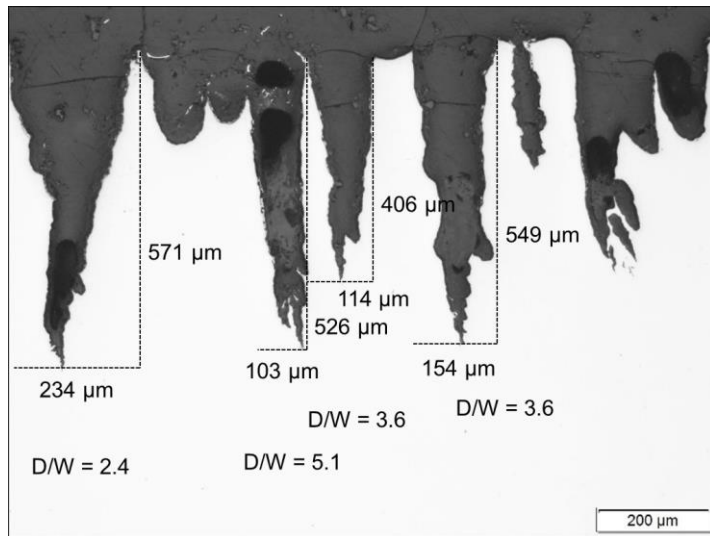
- X  $\text{H}_2\text{S}$  partial pressure, expressed in kilopascals
- Y in situ pH
- 0 region 0
- 1 SSC region 1
- 2 SSC region 2
- 3 SSC region 3

NOTE 1 The discontinuities in the figure below 0,3 kPa (0,05 psi) and above 1 MPa (150 psi) partial pressure  $\text{H}_2\text{S}$  reflect uncertainty with respect to the measurement of  $\text{H}_2\text{S}$  partial pressure (low  $p_{\text{H}_2\text{S}}$ ) and the steel's performance outside these limits (for both low and high  $p_{\text{H}_2\text{S}}$ ).

# SSC Test Evaluation – Pitting and Grooving

## Metallographic evaluation of SSC four-point bend test specimens

- Potential initiation of stress-assisted grooving or pitting
- Distinction between SSC cracks and pits as essential evaluation criteria
- Recommended C2020-14845 evaluation criteria flow chart

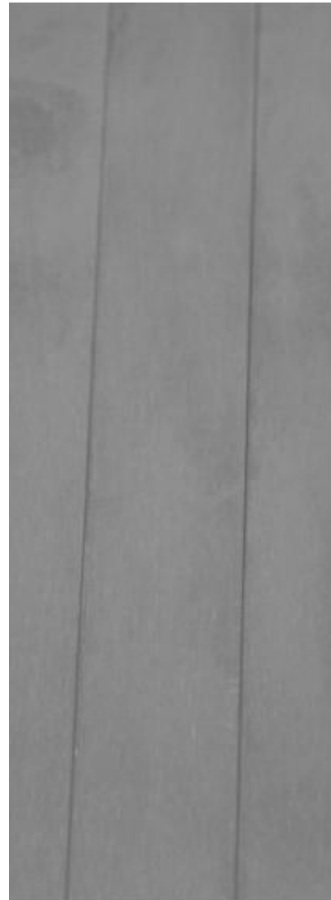




# Influence of CO<sub>2</sub> on SSC test specimens – Learnings from C2021-16571

## SSC Test on X65

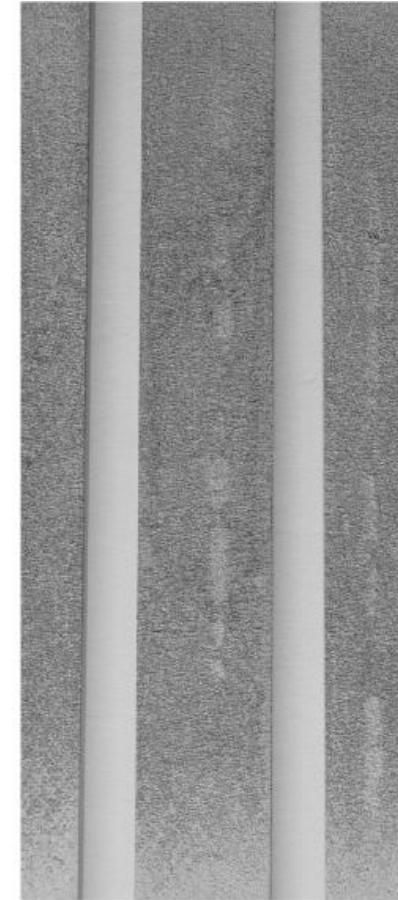
- 1 bar total pressure
- Machined surface
- 100 % CO<sub>2</sub> to 100 % H<sub>2</sub>S
- Effect of CO<sub>2</sub> content in test environment on surface roughness



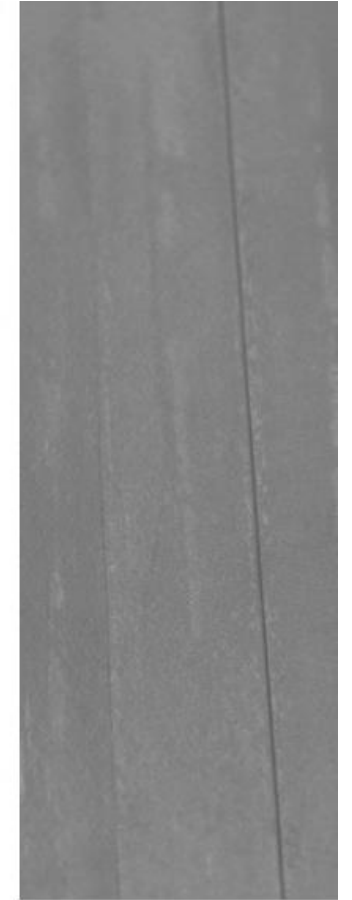
100 % CO<sub>2</sub>



0,3 % H<sub>2</sub>S in CO<sub>2</sub>



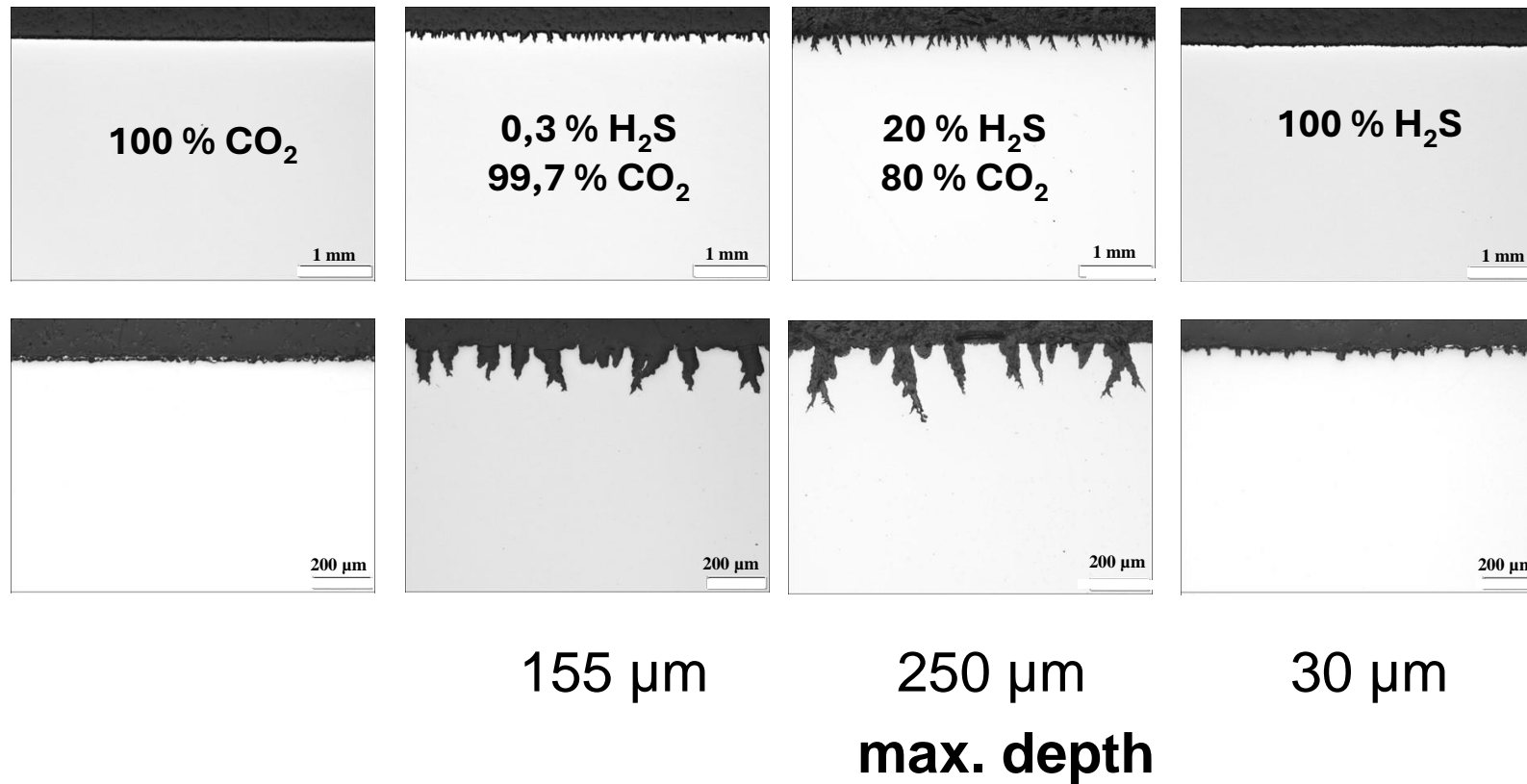
20 % H<sub>2</sub>S in CO<sub>2</sub>



100 % H<sub>2</sub>S

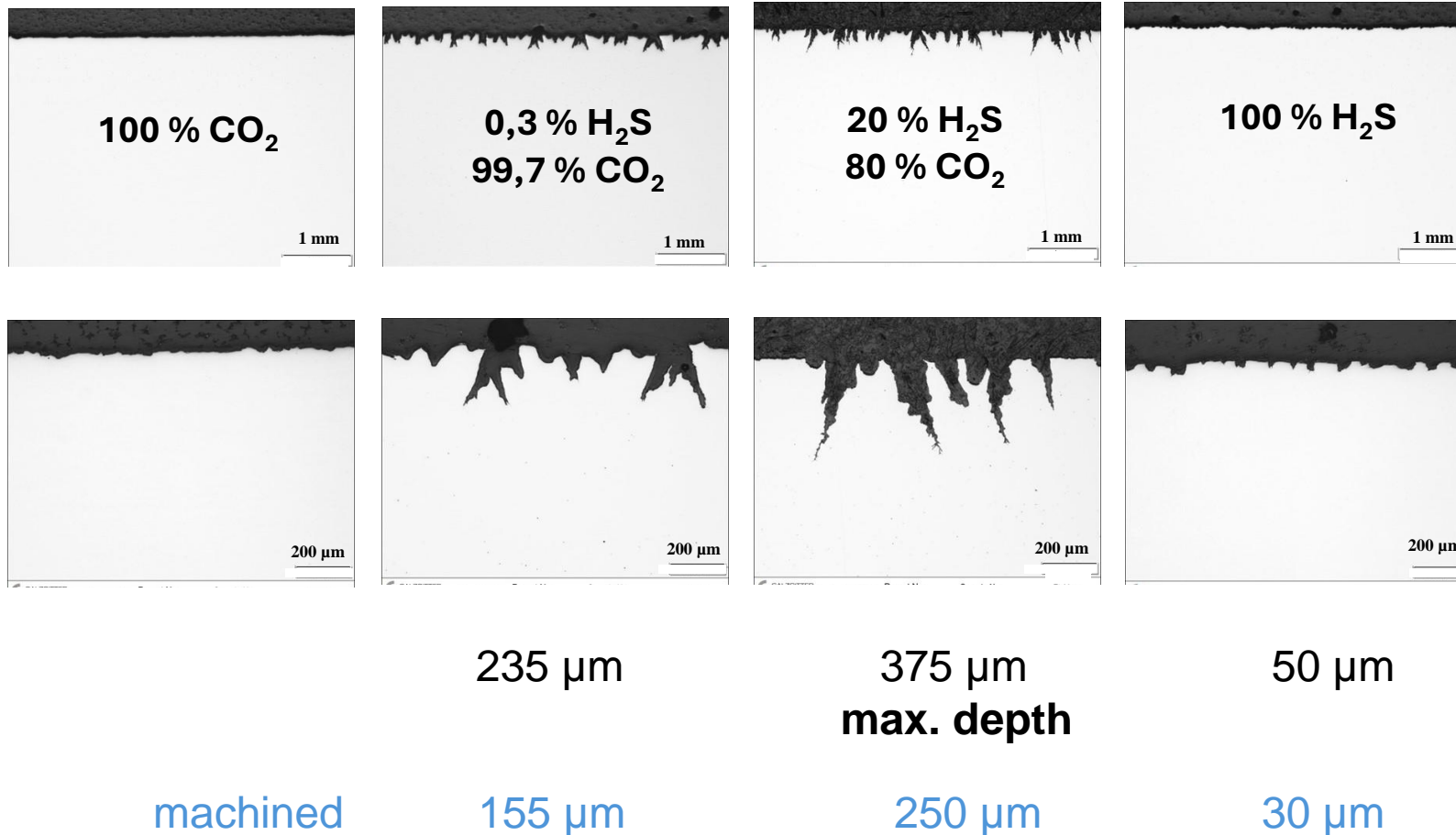
# Influence of CO<sub>2</sub> on SSC test specimens – Learnings from C2021-16571

- SSC tests results for X65 with machined surface (90 % AYS)



# Influence of CO<sub>2</sub> on SSC test specimens – Learnings from C2021-16571

- Tests results for X65 with original surface (90 % AYS)

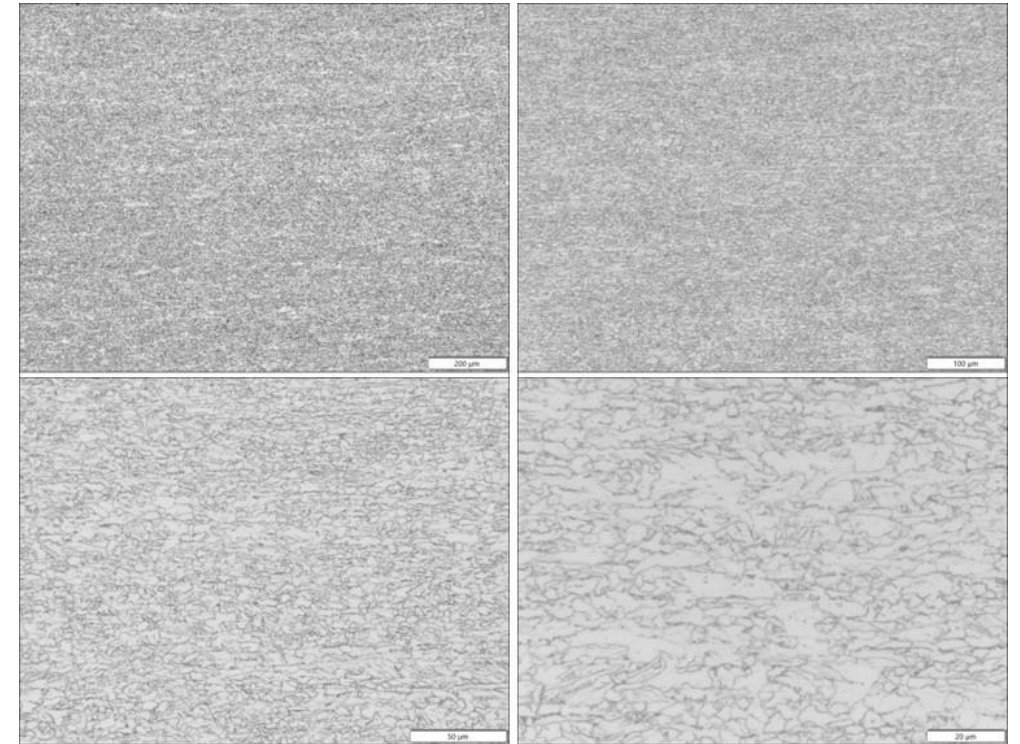




# Investigated Pipe Material

## X65 SAWL large-diameter pipes (TMCP-based)

- OD 812 mm (32") diameter with 25.4 mm and OD 965 mm (38") with 28.8 mm wall thickness
- Eight different pipes / heats covered
- Average base material hardness
  - 0.25 mm below surface: 226 HV0.1
  - 1 mm below surface: 227 HV0.1 / 209 HV10
- Fully HIC resistant material with bainitic microstructure
- Chemical analysis with low C and Mn



Chemical Analysis [Weight %]

|      | C    | Si   | Mn   | P     | S     | Ni   | Nb + V + Ti | Others |
|------|------|------|------|-------|-------|------|-------------|--------|
| Pipe | 0.04 | 0.26 | 1.42 | 0.006 | 0.001 | 0.44 | 0.04        | Cu, Cr |

# SSC Test Conditions

## Four-point bend specimens (140 mm x 15 mm x 5 mm)

- Longitudinal base material specimens, machined with intact pipe inside surface
- Weld specimens transverse to longitudinal weld, fully machined

## SSC tests in autoclave, six test conditions

- Load 90 % AYS (AYS: 481 - 530 MPa), at ambient temperature (25 °C)

| Test condition | p H <sub>2</sub> S | p CO <sub>2</sub> | Load % AYS | Test solution | pH      | Test duration |
|----------------|--------------------|-------------------|------------|---------------|---------|---------------|
|                | [bar]              | [bar]             |            |               |         |               |
| A              | 1.0                | 0.0               | 90         | TM0177 A      | 2.7-4.0 | 720 h         |
| B              | 3.3                | 6.0               | 90         | TM0177 B      | 3.5     | 720 h         |
| C              | 7.0                | 3.0               | 90         | TM0177 B      | 3.5     | 720 h         |
| D              | 12.0               | 3.0               | 90         | TM0177 B      | 3.5     | 720 h         |
| E              | 16.0               | 1.0               | 90         | TM0177 B      | 3.5     | 720 h         |
| F              | 16.0               | 5.0               | 90         | TM0177 B      | 3.5     | 720 h         |

- pH adjusted before test start; Oxygen below 10 ppb
- Re-pressurization if pressure drop  $\geq 0.5$  bar

# SSC Test Results - Overview

## Results of Evaluation

- Visual evaluation and wet magnetic particle inspection (MPI)
- Sectioning at 1/3 and 2/3 width (or crack location) for metallographic evaluation

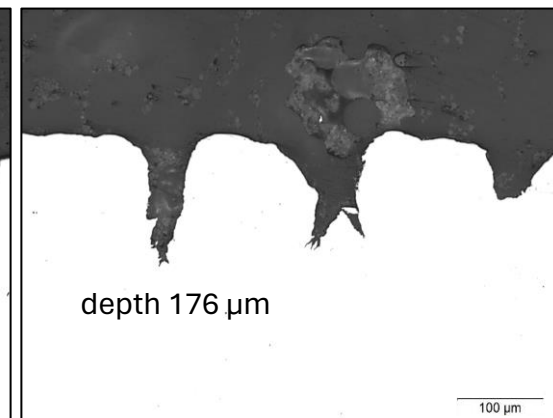
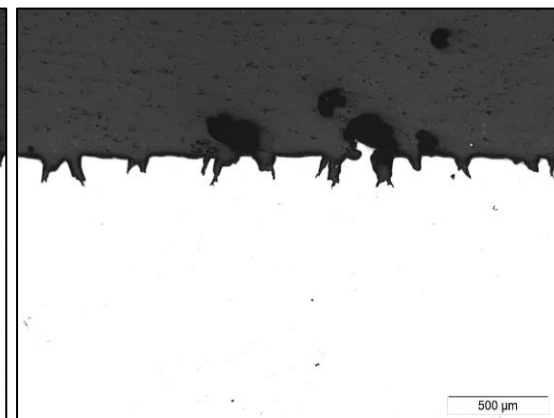
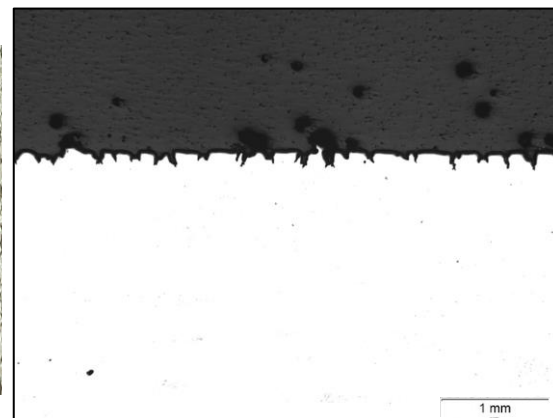
| Test condition | p H <sub>2</sub> S | p CO <sub>2</sub> | Specimen Location | Evaluation           |                                  |
|----------------|--------------------|-------------------|-------------------|----------------------|----------------------------------|
|                | [bar]              | [bar]             |                   | Visual               | Metallographic                   |
| A              | 1.0                | 0.0               | base material     | o.k.                 | Small pits                       |
|                |                    |                   | weld              | o.k.                 | Small pits                       |
| B              | 3.3                | 6.0               | base material     | o.k.                 | SAC / Pits                       |
|                |                    |                   | weld              | o.k.                 | SAC / Pits                       |
| C              | 7.0                | 3.0               | base material     | o.k.                 | SAC / Pits                       |
|                |                    |                   | weld              | small HIC Blister    | SAC / Pits                       |
| D              | 12.0               | 3.0               | base material     | HIC Blister          | HIC Blister + SAC / Pits         |
|                |                    |                   | weld              | HIC Blister          | HIC Blister (BM) / SAC / Pits    |
| E              | 16.0               | 1.0               | base material     | HIC Blister          | HIC Blister + SAC / Pits         |
|                |                    |                   | weld              | multiple HIC Blister | multiple SOHIC (BM) + SAC / Pits |
| F              | 16.0               | 5.0               | base material     | broken HIC Blister   | deep HIC Blisters + SAC / Pits   |
|                |                    |                   | weld              | multiple HIC Blister | SOHIC (BM) + SAC / Pits          |

- SAC: Stress-Assisted Corrosion

# SSC Test Results - Details

## Up to 7 bar H<sub>2</sub>S / 3 bar CO<sub>2</sub>

- No visible surface features other than SAC and pits for base material
- Depth of SAC / pits in general below 200 µm

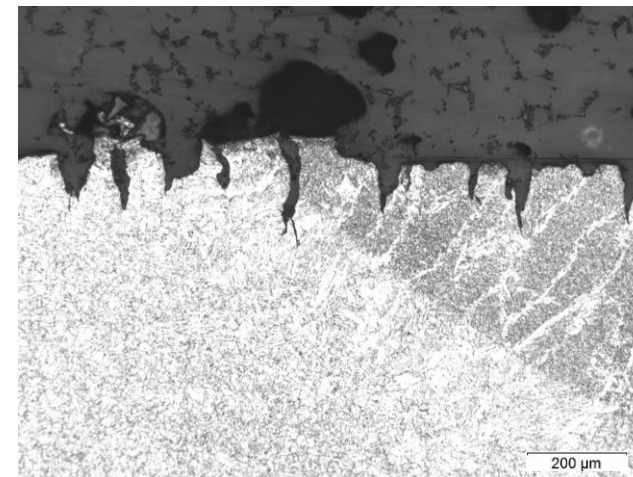
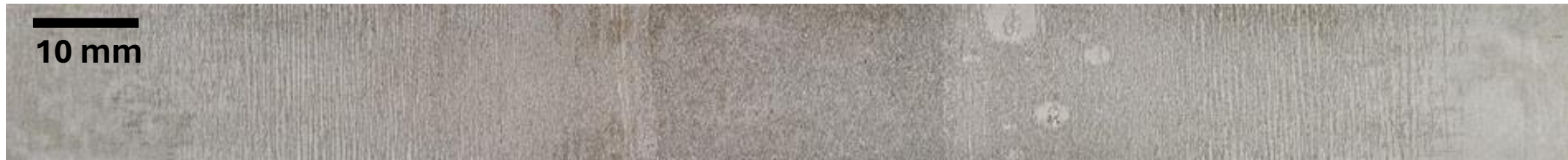




# SSC Test Results - Details

## Up to 7 bar H<sub>2</sub>S / 3 bar CO<sub>2</sub>

- For weld specimens small HIC blisters in base material area of specimens
- SAC / pit characteristics comparable in base and weld material



# SSC Test Results - Details

**12 bar H<sub>2</sub>S / 3 bar CO<sub>2</sub>**

- HIC blisters formed in base material specimens

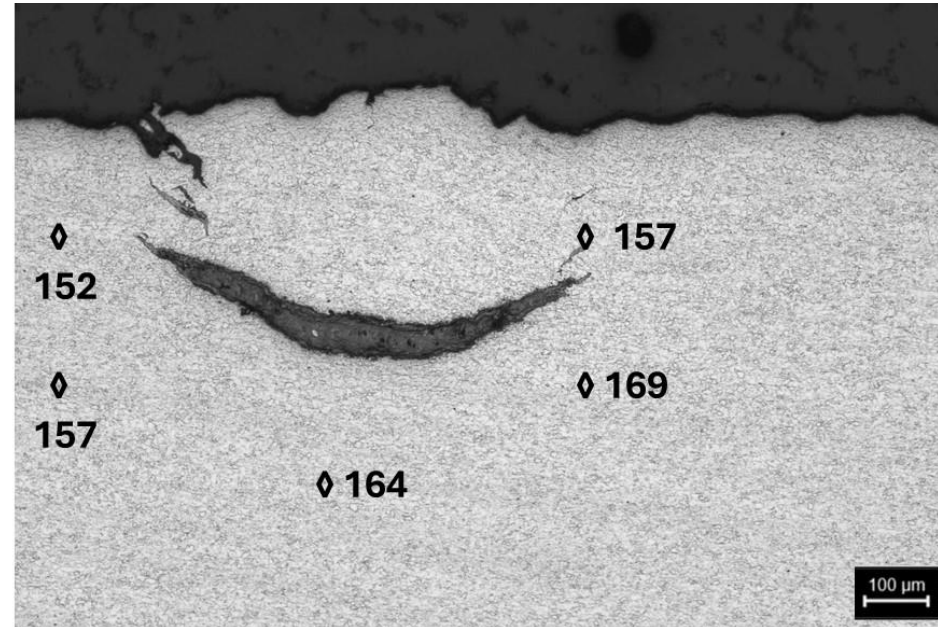
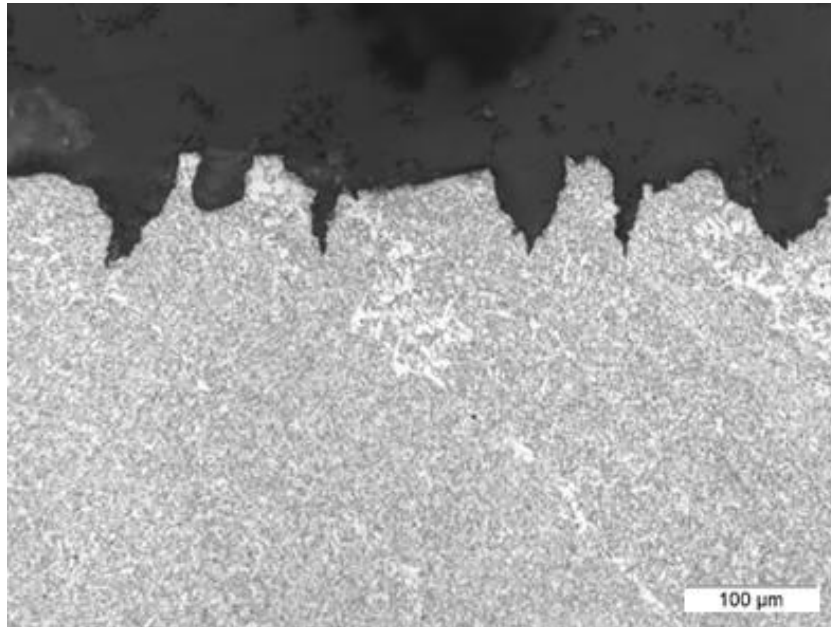
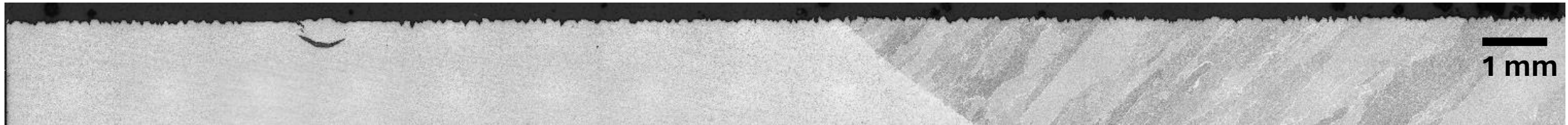




# SSC Test Results - Details

**12 bar H<sub>2</sub>S / 3 bar CO<sub>2</sub>**

- HIC blisters formed in base material portions of weld specimens



◇ HV0.1

# SSC Test Results - Details

## 16 bar H<sub>2</sub>S / 1 bar CO<sub>2</sub>

- Tendency to blistering intensified, especially in base material of weld specimens
- Formation of SOHIC below blisters close to the heat-affected zone of the weld specimens

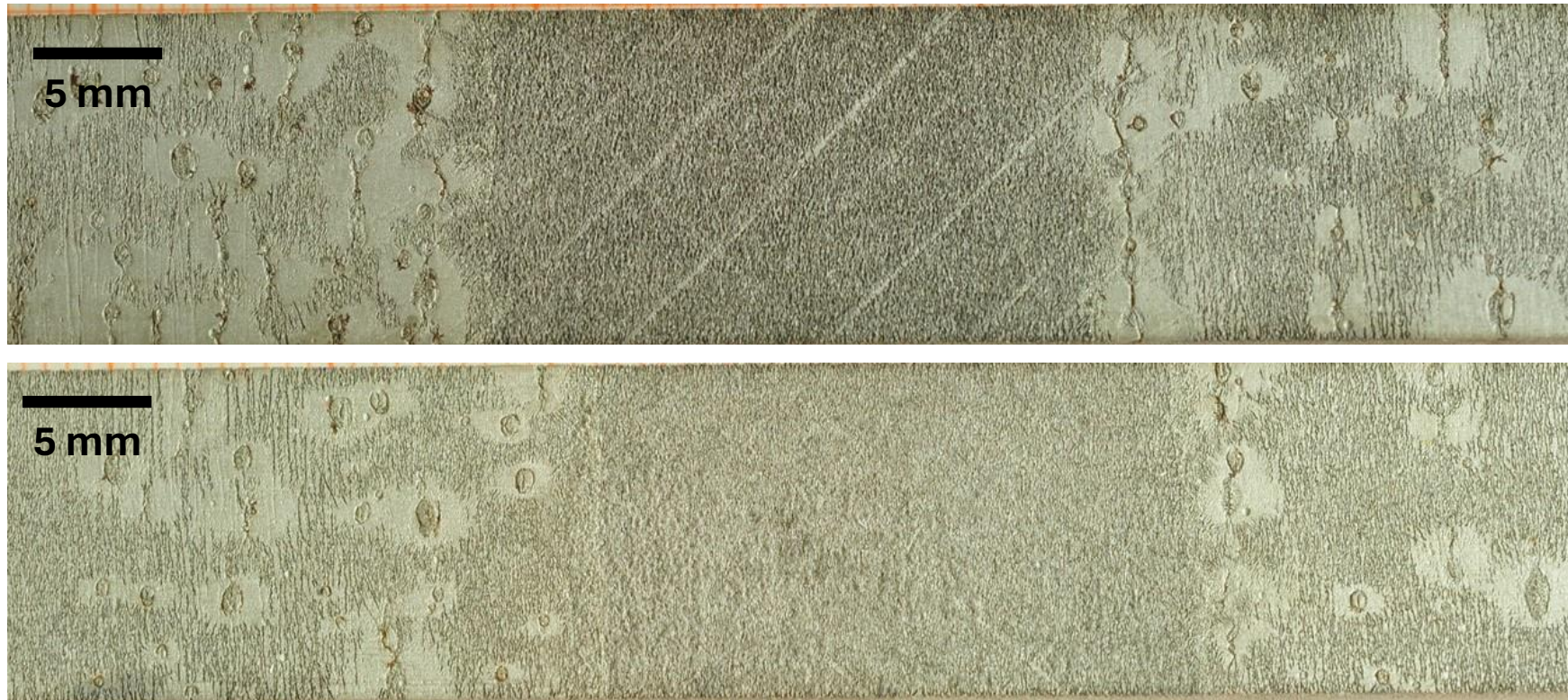




# SSC Test Results – Influence of CO<sub>2</sub>

## 16 bar H<sub>2</sub>S / 1 bar CO<sub>2</sub>

- High Tendency to blistering in weld specimens under 1 bar CO<sub>2</sub>





# SSC Test Results - Influence of CO<sub>2</sub>

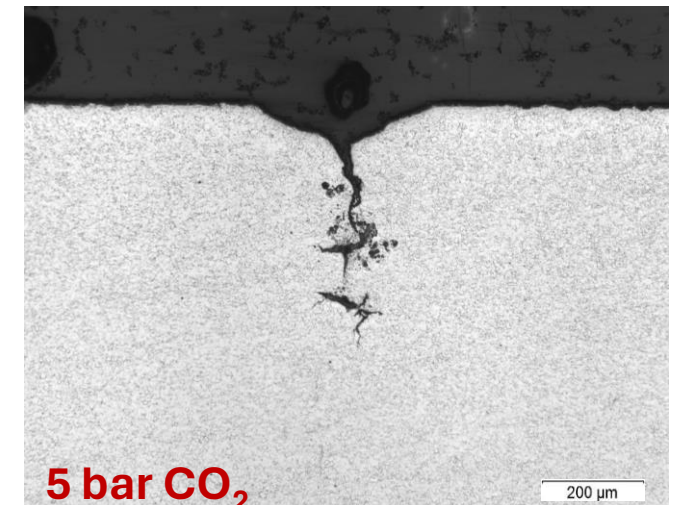
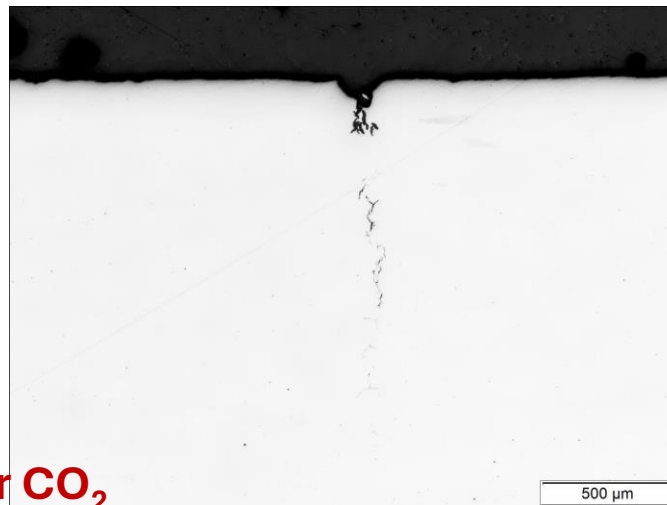
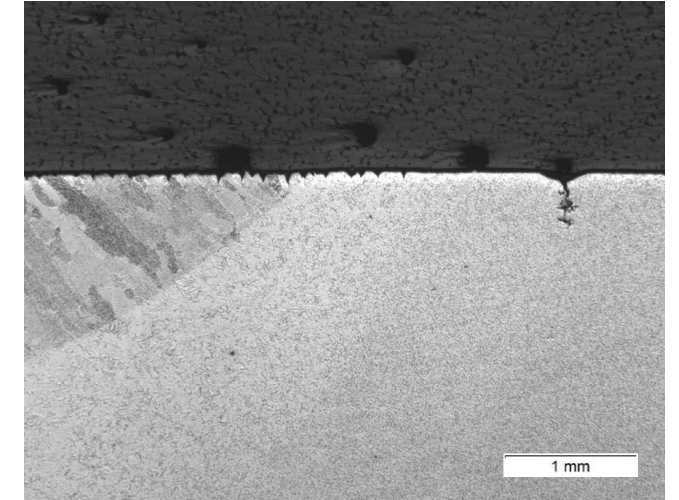
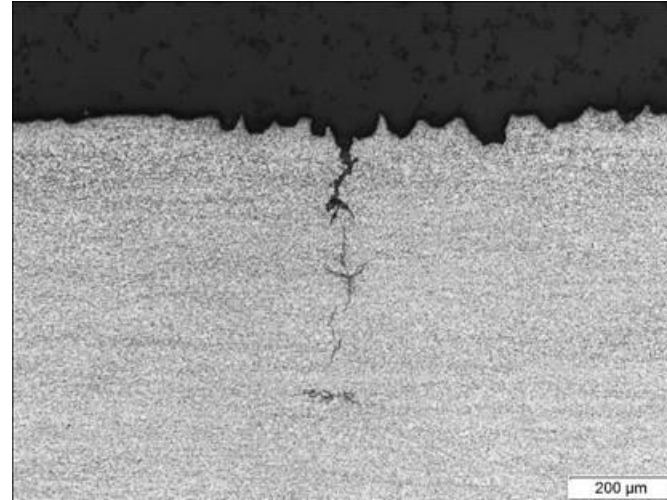
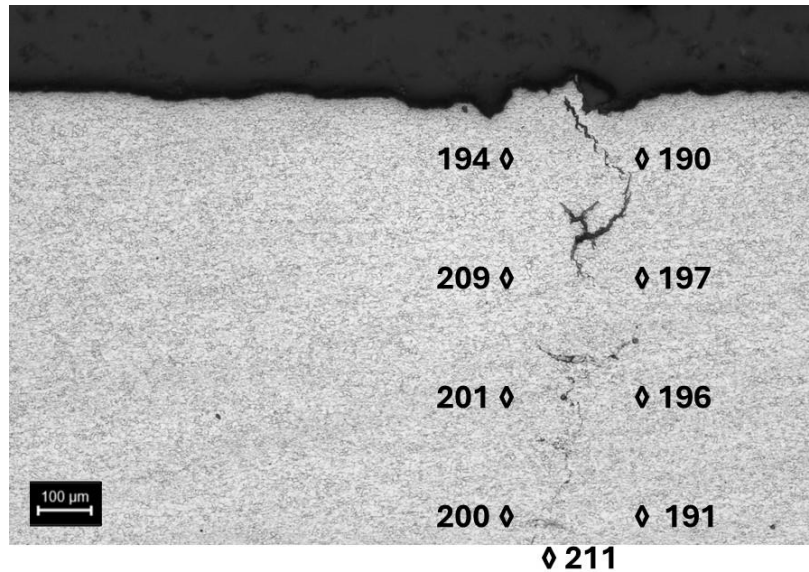
## 16 bar H<sub>2</sub>S / 5 bar CO<sub>2</sub>

- Effect of CO<sub>2</sub> in the pressurized test environment
- Tendency to blistering lower in higher CO<sub>2</sub> environment (1 bar vs. 5 bar)



# SSC Test Results - Influence of CO<sub>2</sub>

- 16 bar H<sub>2</sub>S / 1 bar vs. 5 bar CO<sub>2</sub>
- Formation of **SOHIC** below the blisters
- Depth > 1 mm at 1 bar CO<sub>2</sub>
- Depth reduced at 5 bar CO<sub>2</sub>



1 bar CO<sub>2</sub>

5 bar CO<sub>2</sub>

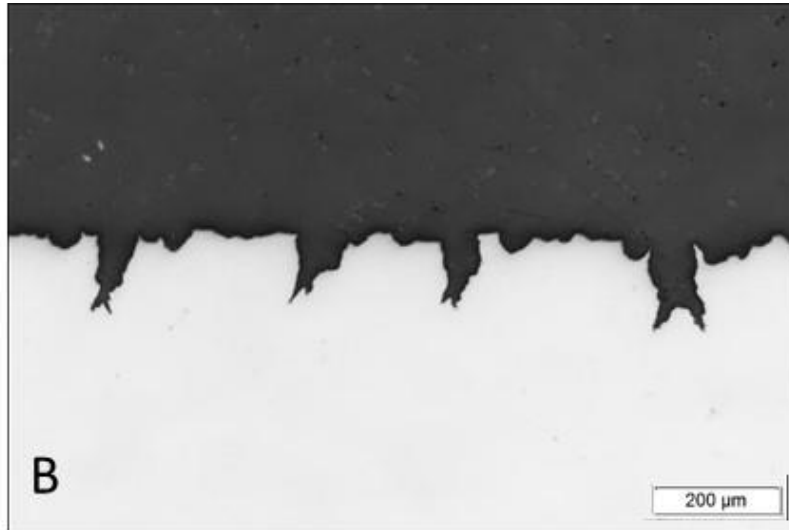


# SSC Test Evaluation for Pits, Grooves and SACs

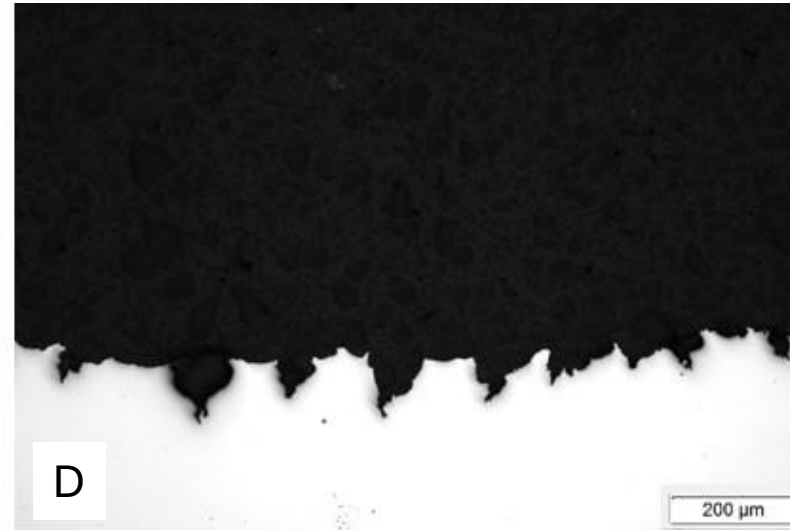
## Metallographic evaluation of SSC test specimens

- Correlation of depth and shape with environmental conditions difficult

3.3 bar H<sub>2</sub>S /  
6 bar CO<sub>2</sub>



12 bar H<sub>2</sub>S /  
3 bar CO<sub>2</sub>



- Depth of nearly all features 150-200 μm max.
- Recommendation to exclude features below threshold (200 μm suggested) from further evaluation for TMCP line pipe steel



# Conclusions

- Results of elevated-pressure SSC autoclave tests have been compared for TMCP line pipe steel.
- Occurrence of stress-assisted pits and grooves independent of test conditions.
- Recommendation to exclude features that extend less than a particular limit from further metallographic evaluation and calculations (200  $\mu\text{m}$  suggested).
- Within region 3 of NACE MR0175/ISO 15156-2 the results indicate a potential border of SSC resistance between 7 bar and 12 bar  $\text{H}_2\text{S}$  partial pressure.
- The effect of the amount of  $\text{CO}_2$  in the test environment is fundamental.
- With increasing  $\text{CO}_2$  partial pressure, the severity of the test environment has been found to decrease.
- Possible combined effect of  $\text{CO}_2$  corrosion and  $\text{H}_2\text{S}$  fugacity.
- Potential influence of lower  $\text{H}_2\text{S}$  fugacity combined with higher general (lower localized)  $\text{CO}_2$  corrosion at higher levels of  $\text{CO}_2$ .
- The level of  $\text{CO}_2$  in the test environment should be considered relevant for SSC testing and should be selected close to intended field conditions.

**Thank You for your Attendance**

