EPRG-PRCI-APGA
23rd Joint Technical Meeting
Edinburgh, Scotland • 6–10 June 2022

# EFFECTS OF CATHODIC OVER PROTECTION ON RESIDUAL STRENGTH OF DAMAGED PIPES

8 June 2022

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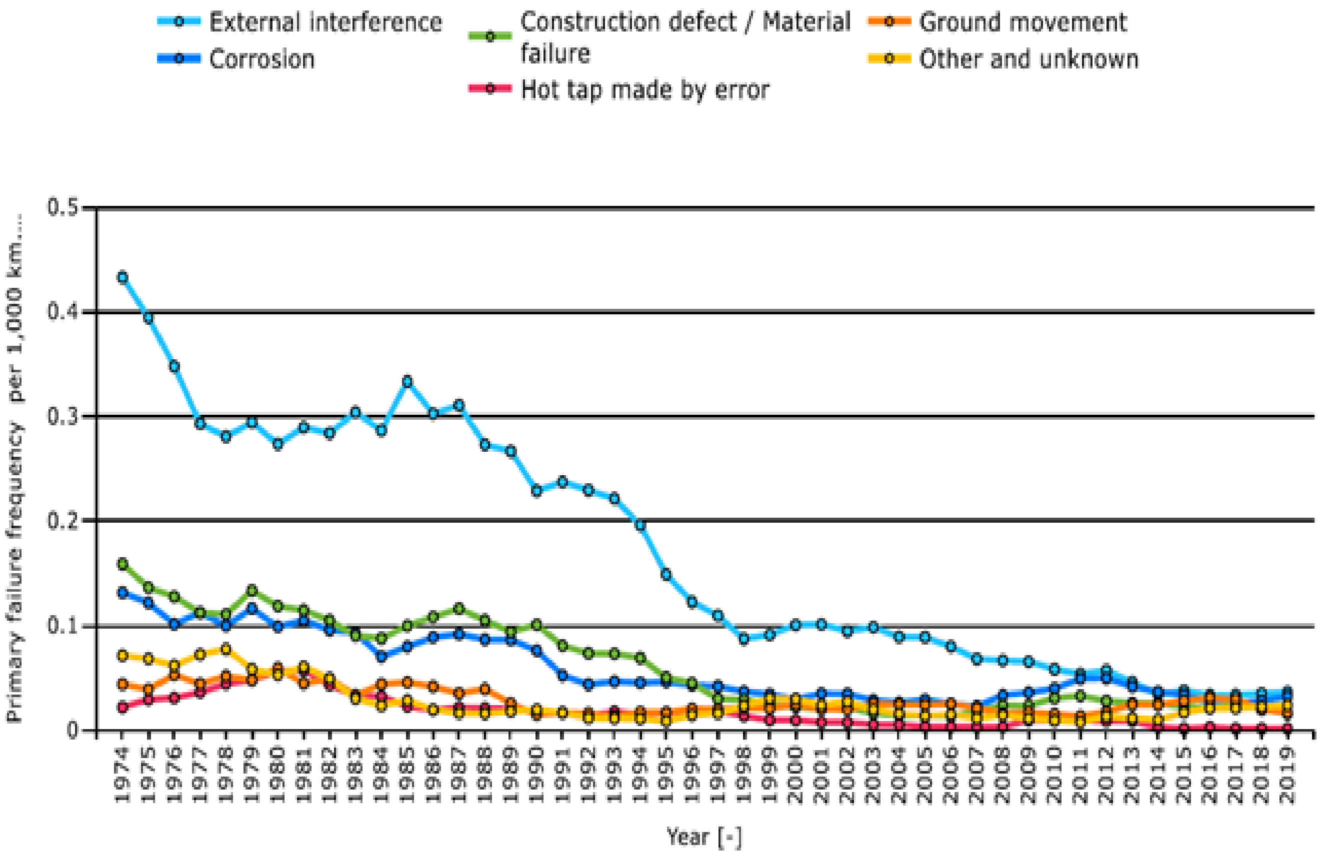
# Content

# Background

*"Incidents caused by external interference [...] are characterized by potentially severe consequences [...] Over the last ten years, external interference [...] represent 27% [...] of the pipeline incidents reported" [1].*

The hydrogen generated by cathodic (over) protection may play an important role, entering inside the material lattice when stresses are applied (internal pressure), causing the local embrittlement of the pipe material and allowing the growth of micro-cracks in the damaged area, which often undergoes a re-transformed microstructure, with higher hardness and lower toughness properties, as a consequence of the damaging process.




1. 11th EGIG report: Gas Pipeline Incidents, Doc. Number EGIG VA 20.0432, December 2020

# Projects

Three full scale projects aimed at reproducing the effect of cathodic (over) protection on pipes with third party damage. Variables investigated were:

- Damage type: gouge or dent&gouge;
- Tooth wear: new or worn;
- Cathodic protection potential: -850, -1150, -1450 mV vs $Cu/CuSO_4$;
- Environment: ground water and brackish water;
- Coating: with or without coating.

# Projects

The full scale tests included:

- Realistic damages;
- Cyclic internal pressure;
- Environment;
- Cathodic protection.

Total of 28 damages and 20 months testing.

# Projects

| Project # | 151 | 174 | 196 |
|---|---|---|---|
| Pipes | 2 LSAW, X70, 48”OD x 17,5mm WT | 2 LSAW, X70, 48”OD x 17,5mm WT | 1 HSAW, X70, 48”OD x 17,5mm WT |
| Total number of damages | 16 | 8 | 4 |
| Type of damages | Dent&gouge + gouge | Dent&gouge | Dent&gouge |
| Coating | 3LPE | 3LPE | No coating |
| Simulated excavator (ton) | 35 | 35 | 35 |
| Excavator tooth | New and worn | New | New |
| Cathodic protection potential vs $Cu/CuSO_4$ (mV) | -850 and -1450 | -1150 and -1450 | -1450 |
| Environment | Ground water and brackish water | Ground water | Ground water |
| Max pressure (bar) | 100 | 100 | 100 |
| Min pressure (bar) | 90 | 90 | 90 |
| R ($P_{min}$ / $P_{max}$) | 0,9 | 0,9 | 0,9 |
| UF (hoop stress / SMYS) (%) | 72 | 72 | 72 |
| Strain rate | ~ $6,0 \times 10^{-8}$ | ~ $6,0 \times 10^{-8}$ | ~ $6,0 \times 10^{-8}$ |
| Testing time (months) | ~4 | ~8 | ~8 |
| Total number of cycles | ~3600 | ~9000 | ~7000 |

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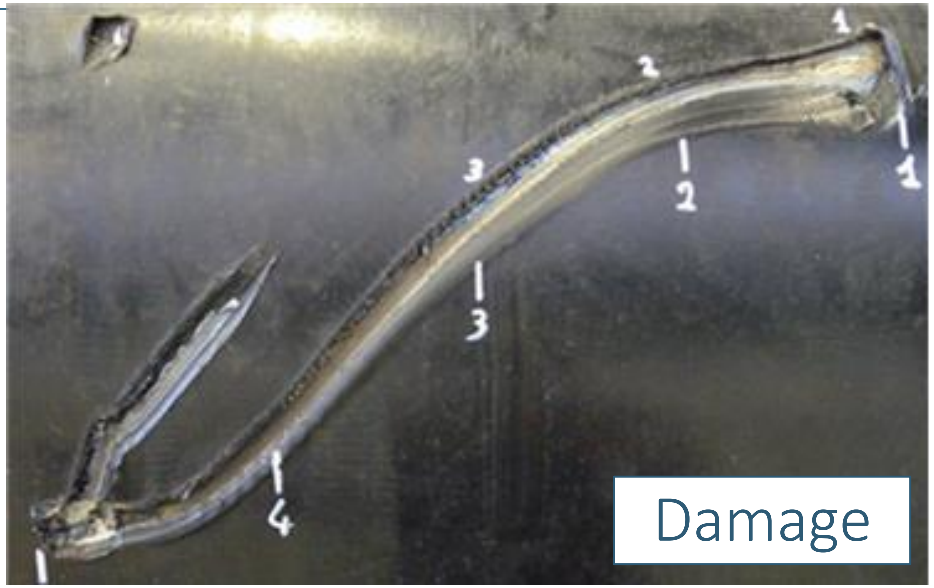
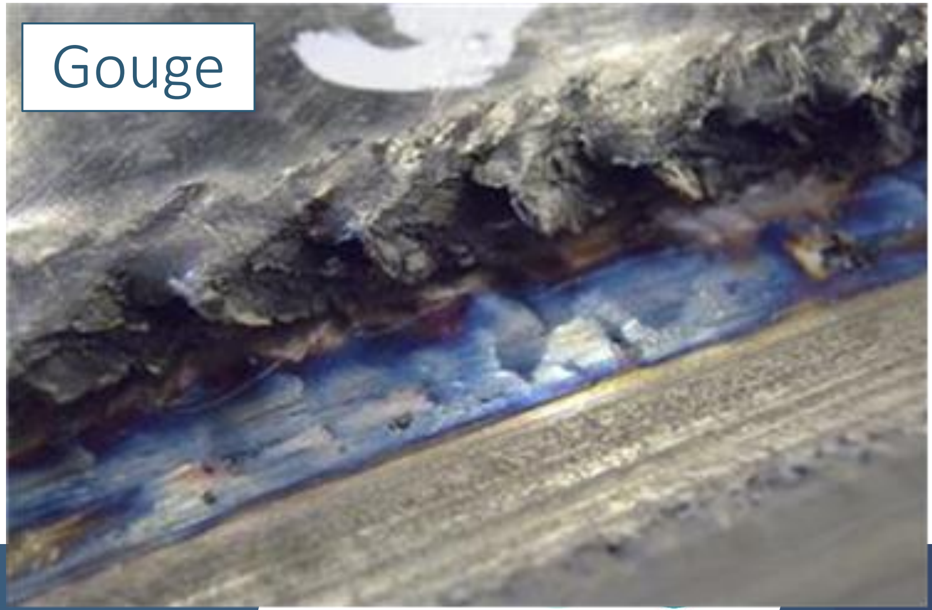
# Mechanical damage

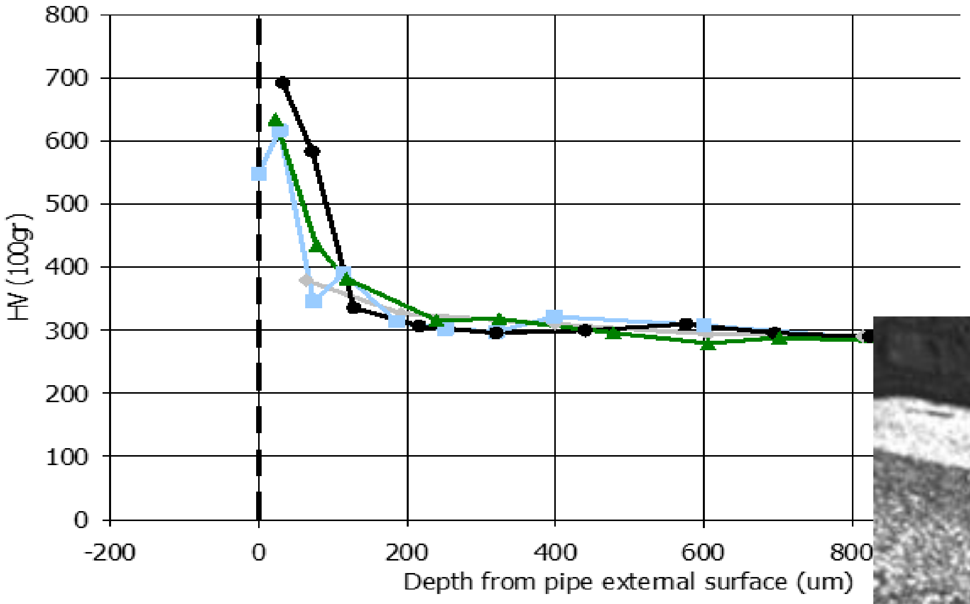



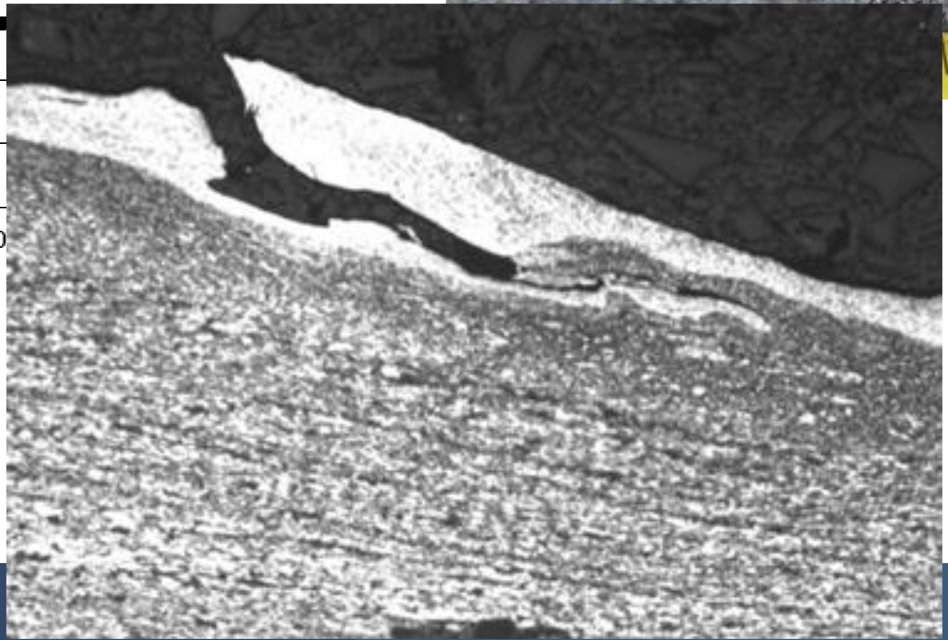
# Mechanical damage

## Damage features after making and before full scale test

Higher hardness material locally




Cracks in the damage



Transformed microstructure in the damaged area

# Mechanical damage

## Damages dimensions

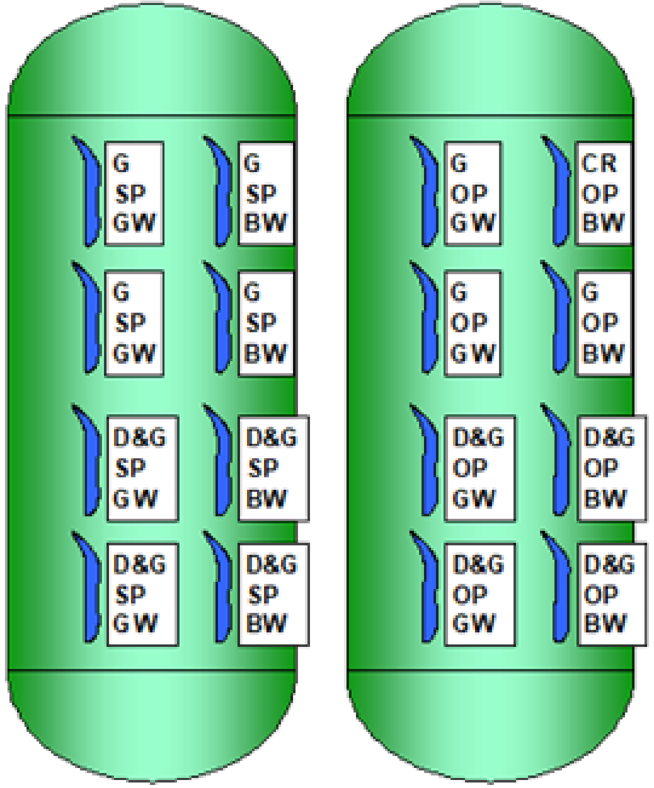
| | | | BG1 | BG2 | BG3 | BG4 | G1 | G2 | G3 | CR1 |
|---|---|---|---|---|---|---|---|---|---|---|
| Pipe 1 | Damage type | | Dent&gouge | | | | Gouge | | | CR |
| | Dent (mm) | Depth | 6,7 | 6,0 | 6,0 | 6,8 | < 1,0 | < 1,0 | < 1,0 | ----- |
| | Gouge* (mm) | Depth 1 | 5,6 | 5,6 | 5,6 | 5,4 | 5,6 | 5,6 | 5,4 | ----- |
| | | Depth 2 | 5,6 | 5,8 | 5,7 | 5,6 | 5,7 | 5,9 | 5,5 | ----- |
| | | Length | 450 | 460 | 440 | 450 | 440 | 440 | 440 | ----- |
| Pipe 2 | | | BG1 | BG2 | BG3 | BG4 | G1 | G2 | G3 | G4 |
| | Damage type | | Dent&gouge | | | | Gouge | | | |
| | Dent (mm) | Depth | 5,5 | 5,1 | 8,0 | 5,4 | < 1,0 | < 1,0 | < 1,0 | < 1,0 |
| | Gouge* (mm) | Depth 1 | 5,1 | 5,0 | 4,5 | 4,8 | 4,7 | 5,0 | 5,2 | 5,2 |
| | | Depth 2 | 4,3 | 4,5 | 4,5 | 5,2 | 4,1 | 5,1 | 4,6 | 5,4 |
| | | Length | 470 | 440 | 462 | 450 | 455 | 470 | 455 | 450 |

*: Gouge depth including coating thickness, about 4 mm and not constant.

| | | | BG1 | BG2 | BG3 | BG4 |
|---|---|---|---|---|---|---|
| Pipe 3 | Damage type | | Dent&gouge | | | |
| | Dent (mm) | Depth | 1,9 | 1,5 | 1,8 | 2,0 |
| | Gouge (mm) | Depth 1 | 0,5 | 0,5 | 0,6 | 0,9 |
| | | Depth 2 | 0,6 | 0,8 | 0,7 | 0,6 |
| | | Length | 460 | 470 | 450 | 470 |
| Pipe 4 | | | BG1 | BG2 | BG3 | BG4 |
| | Damage type | | Dent&gouge | | | |
| | Dent (mm) | Depth | 2,5 | 1,9 | 2,7 | 3,0 |
| | Gouge (mm) | Depth 1 | 0,4 | 0,3 | 0,5 | 1,0 |
| | | Depth 2 | 0,4 | 0,4 | 0,4 | 0,6 |
| | | Length | 450 | 450 | 460 | 450 |
| Pipe 5 | Damage type | | Dent&gouge | | | |
| | Dent (mm) | Depth | 3,4 | 4,1 | 3,7 | 3,6 |
| | Gouge (mm) | Depth 1 | 0,5 | 0,4 | 1,0 | 0,9 |
| | | Depth 2 | 1,6 | 1,6 | 1,5 | 1,3 |
| | | Length | 455 | 470 | 470 | 460 |

# Full Scale Tests

Each pipe has a number of damages, one cell per damage with its own environment, cathodic protection potential, electrode and sensors.



# Full Scale Tests

**Pipe 1**

| | | BG1 | BG2 | BG3 | BG4 | G1 | G2 | G3 | CR1 |
|---|---|---|---|---|---|---|---|---|---|
| Damage type | | Dent&gouge | | | | Gouge | | | C.R. |
| Potential vs $Cu/CuSO_4$ (mV) | Target | -1450 | | | | | | | |
| | Actual mean | -1378 | -1370 | -1446 | -1401 | -1338 | -1432 | -1383 | -1131 |
| Current density ($mA/cm^2$) | Target | 2,0 – 4,0 | | | | | | | |
| | Actual mean | 3,5 | 3,6 | 3,6 | 3,5 | 3,6 | 3,6 | 3,5 | 0,8 |
| Environment | | G. W. | G. W. | G. W. | G. W. | B. W. | B. W. | B. W. | B. W. |

**Pipe 2**

| | | BG1 | BG2 | BG3 | BG4 | G1 | G2 | G3 | G4 |
|---|---|---|---|---|---|---|---|---|---|
| Damage type | | Dent&gouge | | | | Gouge | | | |
| Potential vs $Cu/CuSO_4$ (mV) | Target | -850 | | | | | | | |
| | Actual mean | -823 | -838 | -850 | -846 | -842 | -829 | -838 | -842 |
| Current density ($mA/cm^2$) | Target | $10^{-2}$ | | | | | | | |
| | Actual mean | 0,013 | 0,017 | 0,014 | 0,013 | 0,014 | 0,015 | 0,014 | 0,003 |
| Environment | | G. W. | G. W. | G. W. | G. W. | B. W. | B. W. | B. W. | B. W. |

| | |
|---|---|
| **Temperature (°C)** | 23,8 – 32,9 |
| **Pressure (bar)** | 90 – 100 |
| **Cycles** | 3591 |

# Full Scale Tests

**Pipe 3**

| | | BG1 | BG2 | BG3 | BG4 |
|---|---|---|---|---|---|
| Damage type | | Dent&gouge | | | |
| Potential (mV) Vs $Cu/CuSO_4$ | Target | -1100 | | | |
| | Actual mean | -1129 | -1130 | -1149 | -1120 |
| Current density ($mA/cm^2$) | Target | $10^{-1}$ | | | |
| | Actual mean | 0,4 | 0,4 | 0,3 | 0,4 |
| Environment | | Ground water | | | |

**Pipe 4**

| | | BG1 | BG2 | BG3 | BG4 |
|---|---|---|---|---|---|
| Damage type | | Dent&gouge | | | |
| Potential (mV) Vs $Cu/CuSO_4$ | Target | -1450 | | | |
| | Actual mean | -1476 | -1500 | -1426 | -1469 |
| Current density ($mA/cm^2$) | Target | 2,0 – 4,0 | | | |
| | Actual mean | 4,6 | 4,7 | 4,8 | 4,6 |
| Environment | | Ground water | | | |

| | |
|---|---|
| **Temperature (°C)** | 0,2 – 45,8 |
| **Pressure (bar)** | 90 – 100 |
| **Cycles** | 9015 |

**Pipe 5**

| | | BG1 | BG2 | BG3 | BG4 |
|---|---|---|---|---|---|
| Damage type | | Dent&gouge | | | |
| Potential (mV) Vs $Cu/CuSO_4$ | Target | -1450 | | | |
| | Actual mean | -1410 | -1380 | -1410 | -1370 |
| Current density ($mA/cm^2$) | Target | 2,0 – 4,0 | | | |
| | Actual mean | 2,6 | 2,5 | 2,6 | 2,63 |
| Environment | | Ground water | | | |

| | |
|---|---|
| **Temperature (°C)** | 6,5 – 40,7 |
| **Pressure (bar)** | 90 – 100 |
| **Cycles** | 7000 |

# Post test analysis

NDT were performed after full scale test. Comparison with findings from microstructural analysis.

| Pipe 1 | | | Pipe 2 | | |
|---|---|---|---|---|---|
| **Damage** | **NDT** | **Microstructure** | **Damage** | **NDT** | **Microstructure** |
| **BG1** | No crack | --- | **BG1** | Cracks at end of gouge | Cracks |
| **BG2** | No crack | --- | **BG2** | Cracks in the gouge | Cracks |
| **BG3** | No crack | --- | **BG3** | Cracks at impact point | Cracks |
| **BG4** | Cracks at end of gouge | No crack | **BG4** | Cracks at end of gouge | Cracks |
| **G1** | No crack | --- | **G1** | Cracks at end of gouge | Cracks |
| **G2** | No crack | --- | **G2** | No crack | --- |
| **G3** | Cracks at end of gouge | Cracks | **G3** | Cracks at end of gouge | Cracks |
| **CR1** | No crack | --- | **G4** | No crack | --- |

| Pipe 3 | | | Pipe 4 | | |
|---|---|---|---|---|---|
| **Damage** | **NDT** | **Microstructure** | **Damage** | **NDT** | **Microstructure** |
| **BG1** | Crack in the gouge and at the end of gouge | No crack | **BG1** | Crack at end of gouge | No crack |
| **BG2** | Crack in the gouge | No crack | **BG2** | Crack at end of gouge | Cracks |
| **BG3** | Crack in the gouge and at the end of gouge | No crack | **BG3** | No crack | No cracks |
| **BG4** | Crack in the gouge | No crack | **BG4** | No crack | No cracks |

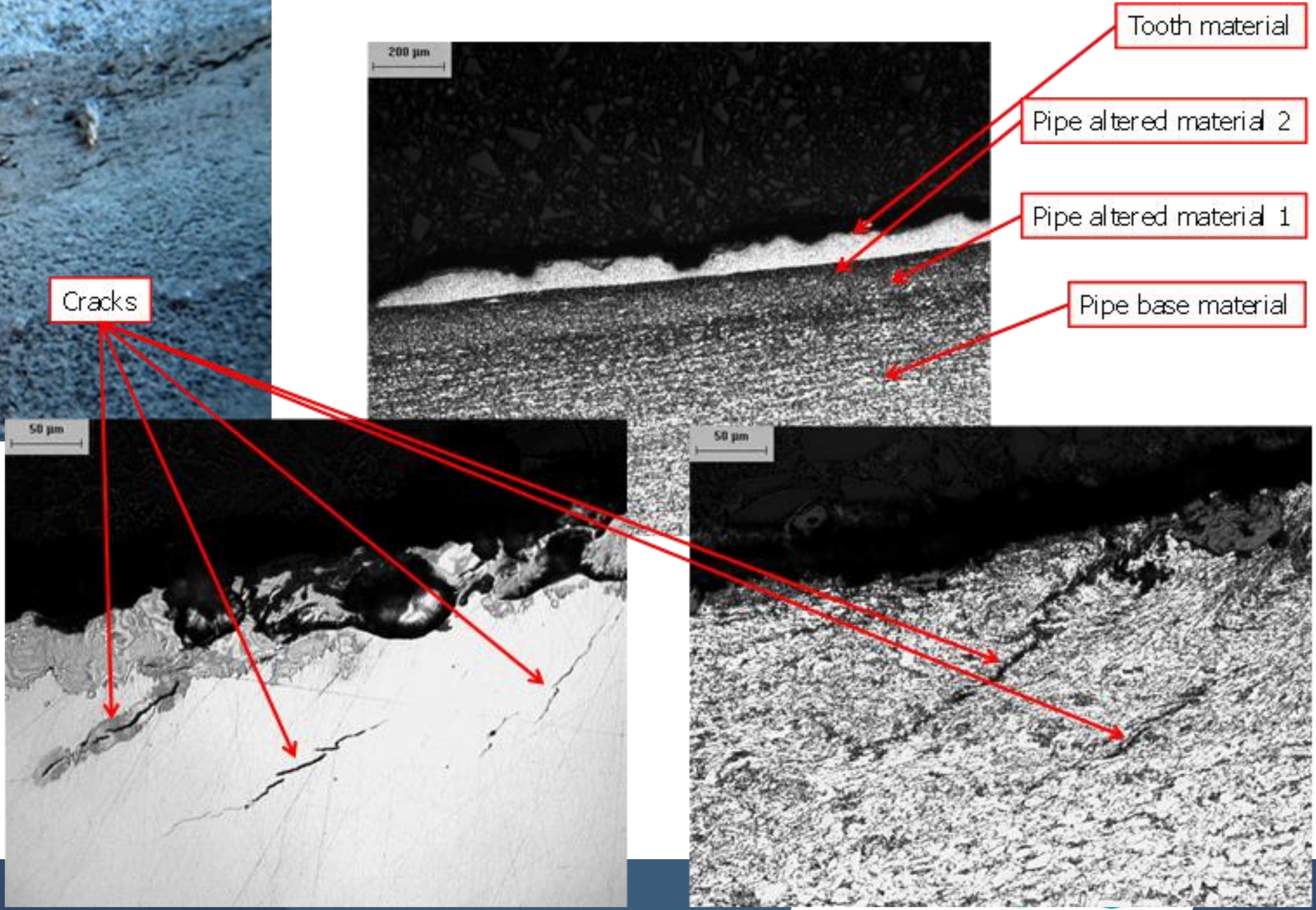
# Post test analysis

On Pipe 5, NDT were performed before and after full scale test. Comparison with findings from microstructural analysis. All indications were confirmed by the microstructural analysis.

Cracks found before full scale test grew, and new cracks were observed in damage BG4.

| Damage | Before full scale test | | | | After full scale test | | | |
|---|---|---|---|---|---|---|---|---|
| | Indications | Type | Dimensions (mm) | Position | Indications | Type | Dimensions (mm) | Position |
| **BG1** | 1 | Group of cracks | 70 | End of gouge | 1 | Group of cracks | 80 | End of gouge |
| **BG2** | 1 | Group of cracks | 50 | End of gouge | 1 | Group of cracks | 80 | End of gouge |
| **BG3** | 1 | Group of cracks | 10 | End of gouge | 1 | Group of cracks | 70 | End of gouge |
| **BG4** | 0 | --- | --- | --- | 2 | Group of cracks | 10 – 80 | Print and end of gouge |

# Post test analysis

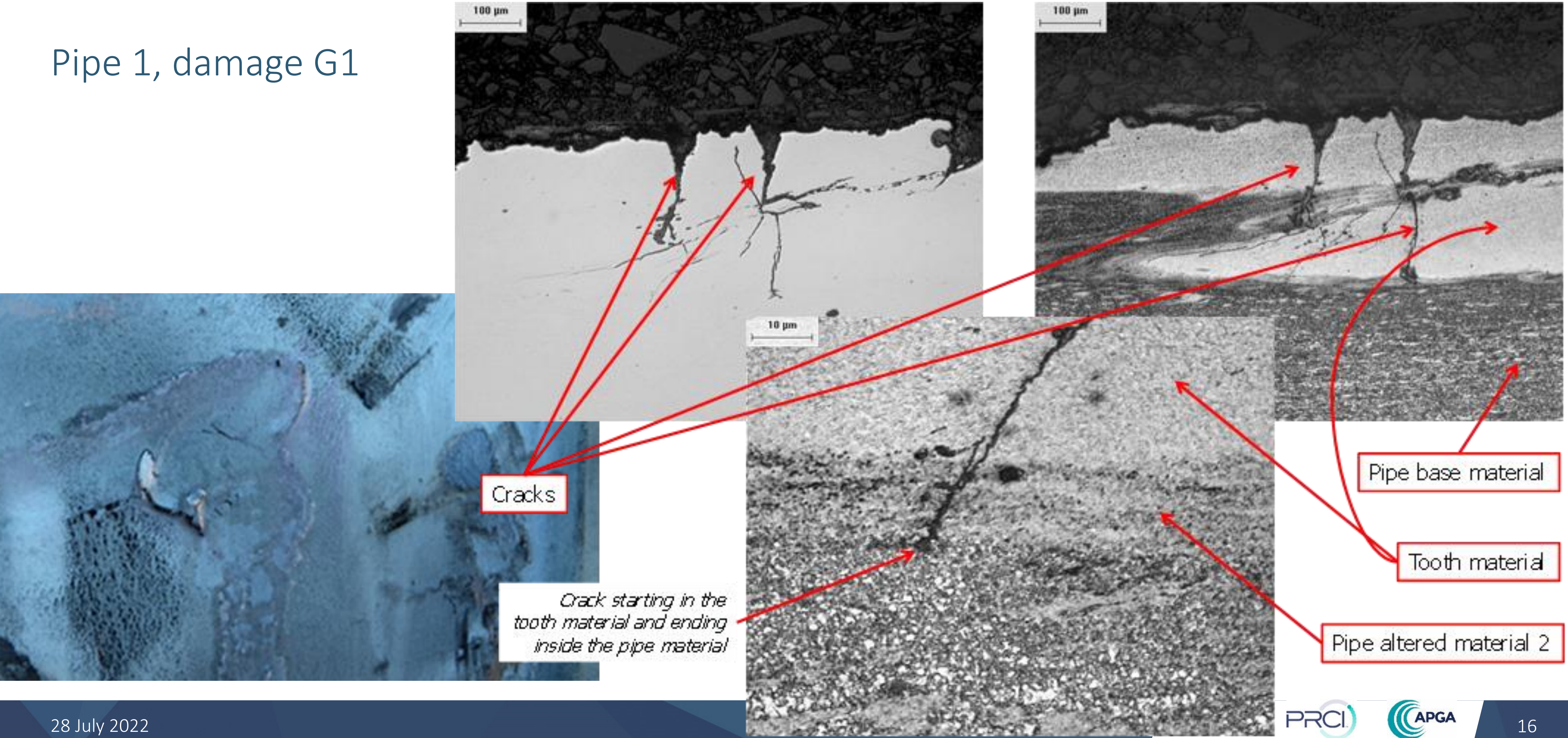



Pipe 1, damage BG2

# Post test analysis

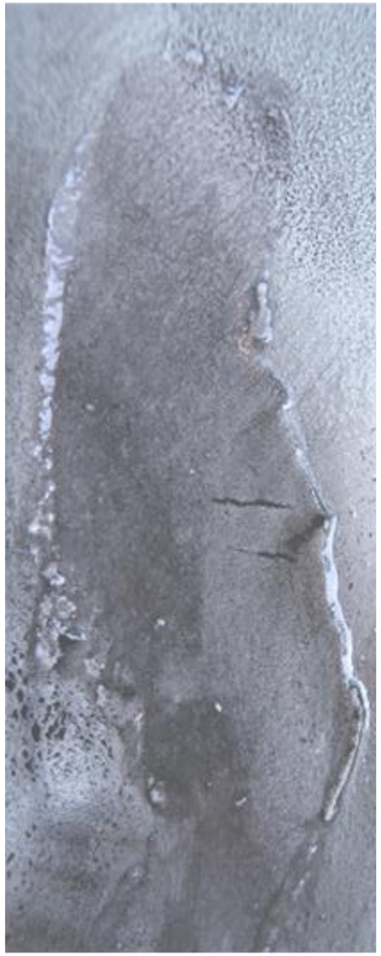


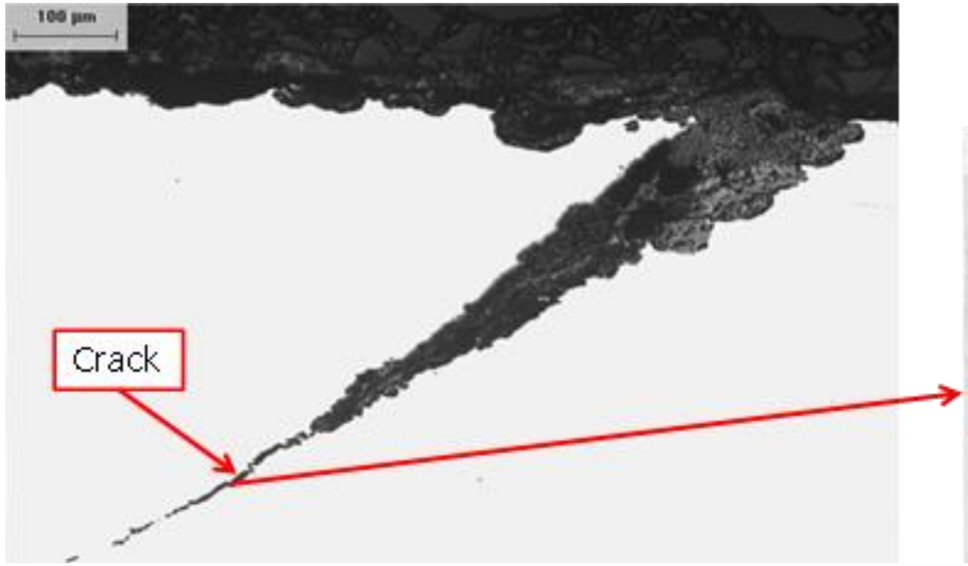
## Pipe 1, damage G1

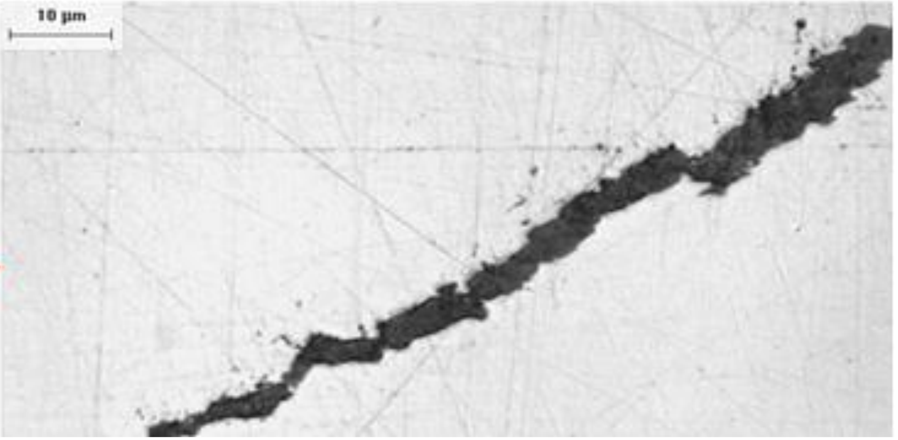


# Post test analysis

## Pipe 1, damage BG3

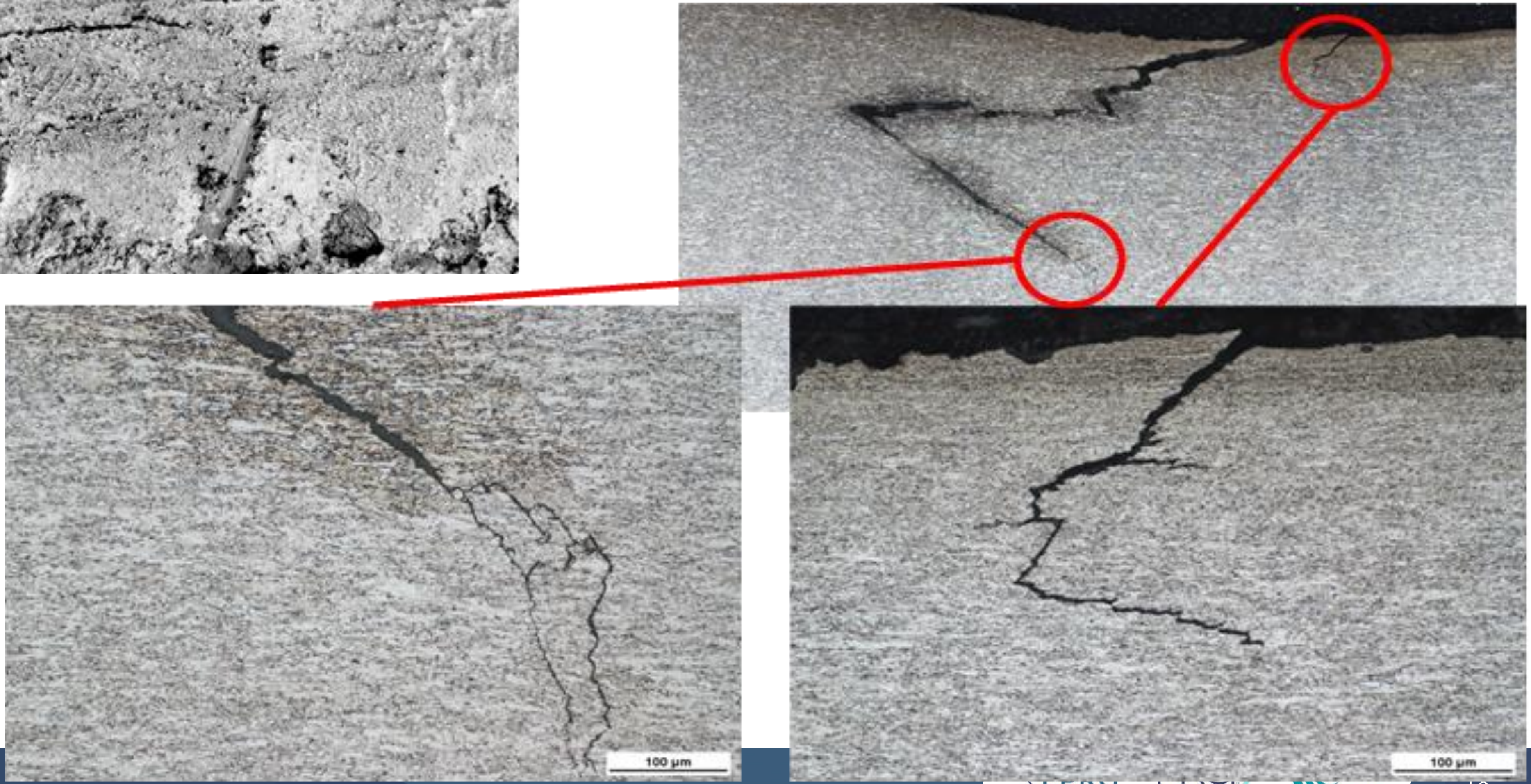




# Post test analysis

## Pipe 5, damage BG1



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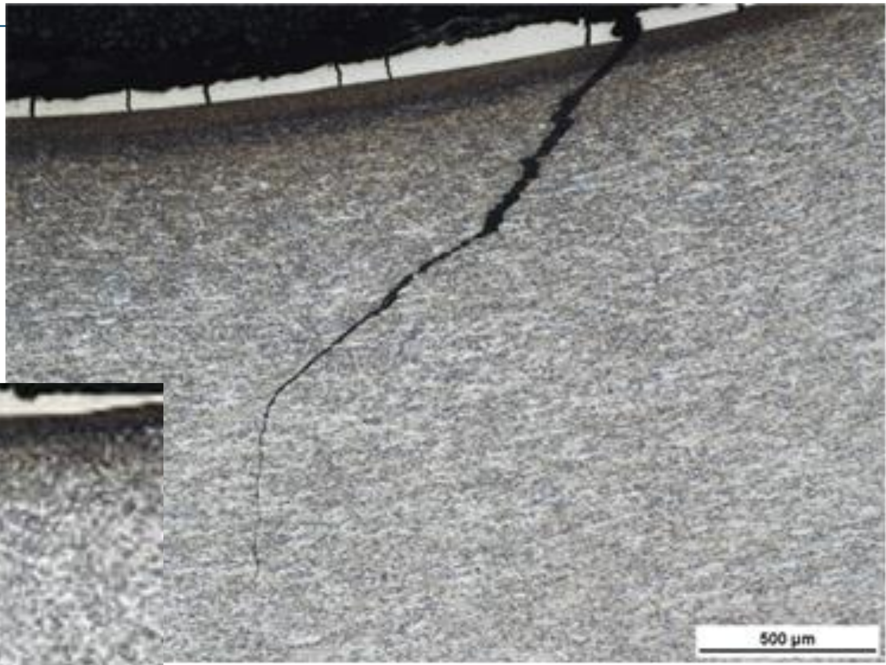
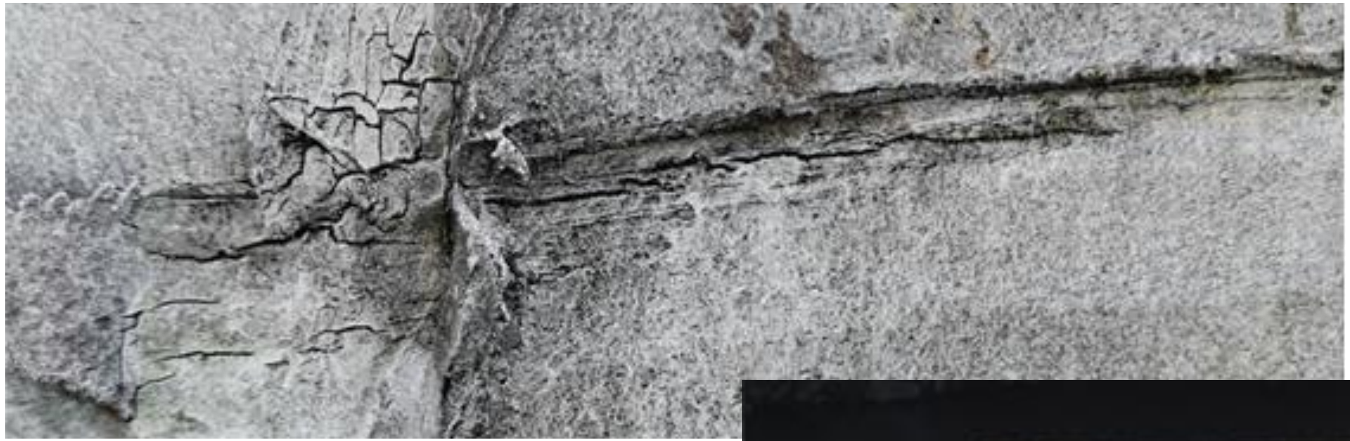
# Post test analysis

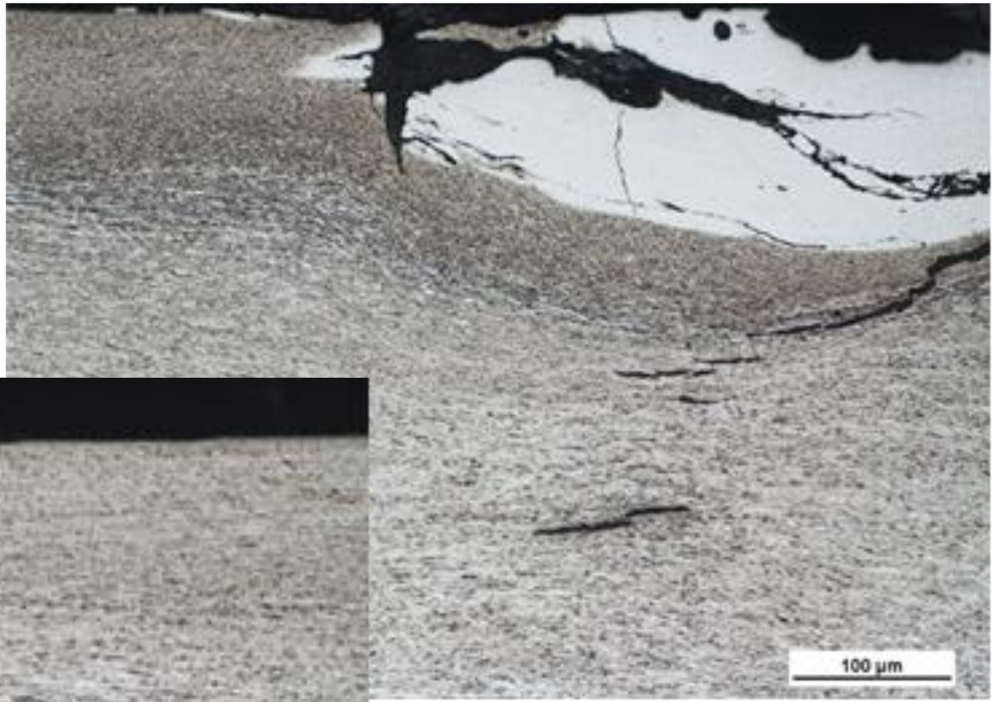



Pipe 5, damage BG2

# Post test analysis







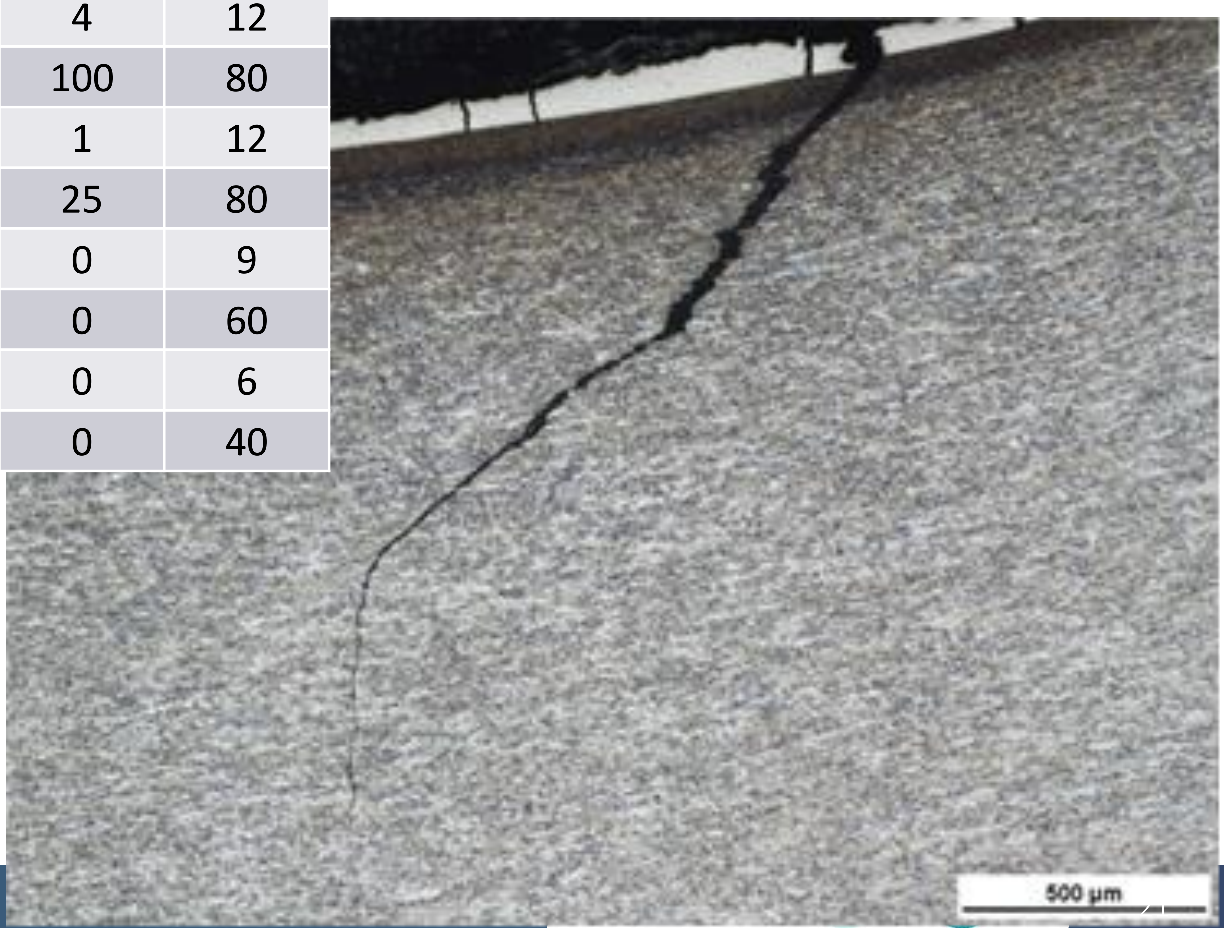


Pipe 5, damage BG4

# Post test analysis

## Statistics on damages

| Potential vs $Cu/CuSO_4$ | mV | -850 | -1150 | -1450 |
|---|---|---|---|---|
| Damages | Total number | 8 | 4 | 15 |
| NDT | Damages with cracks | 2 | 4 | 12 |
| | % | 25 | 100 | 80 |
| Microstructure | Damages with cracks | 1 | 1 | 12 |
| | % | 12,5 | 25 | 80 |
| | Brittle or branched cracks | 0 | 0 | 9 |
| | % | 0 | 0 | 60 |
| | Cracks deeper than hardened layer | 0 | 0 | 6 |
| | % | 0 | 0 | 40 |




40% of damages showed cracks attributable to cathodic over protection (-1450 mV), while at -850 mV and -1150 mV there was no evidence of such effect.

Comparing the cracks depth from external surface, it is found that the depth of the cracks ranges from about 50 µm to about 2,25 mm. Then, the highest estimated crack growth rate is approximately 0,31 µm/cycle.

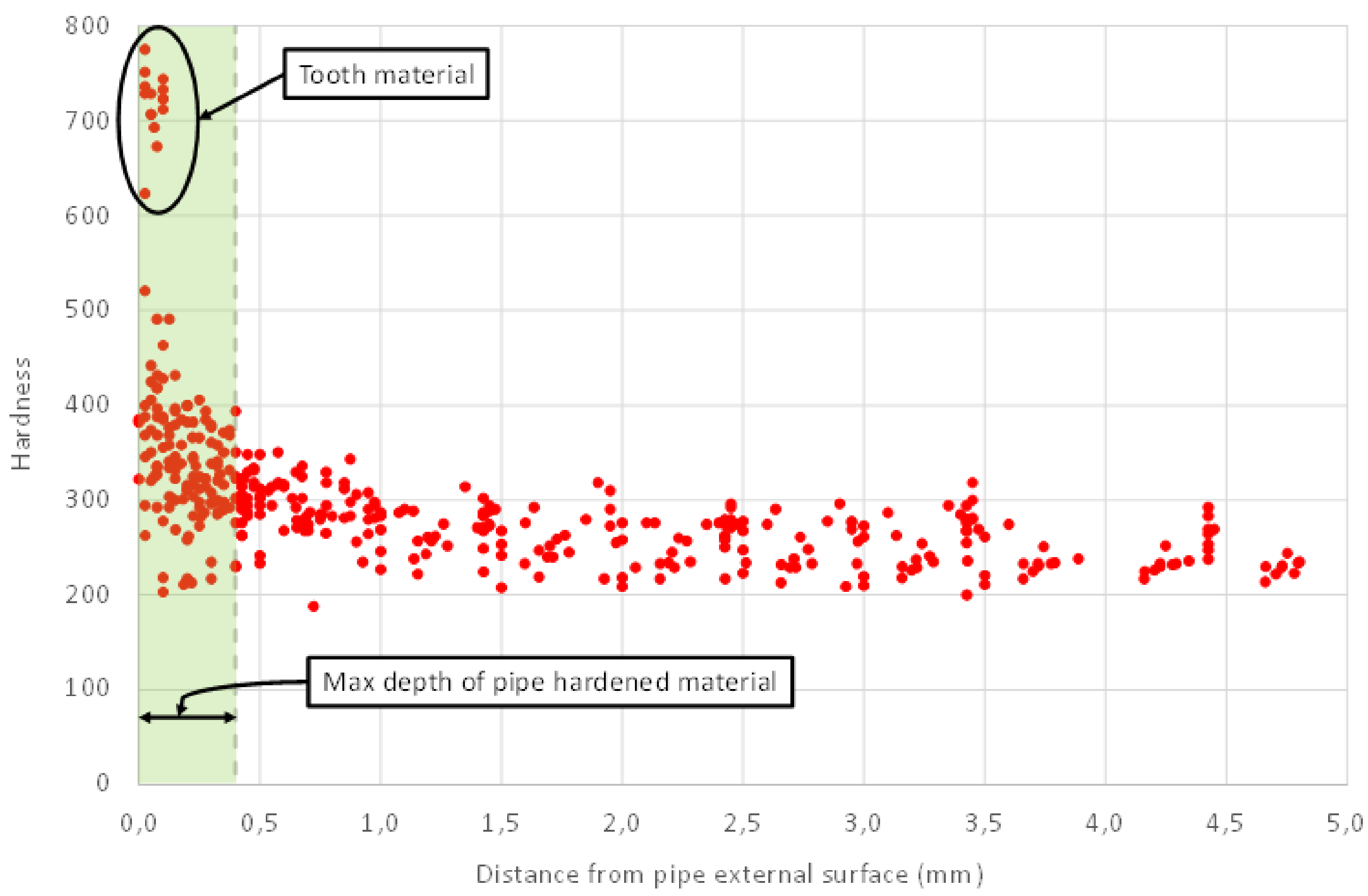
# Post test analysis



## Hardness measurements

It is found that hardness of tooth material is quite higher, above 600 HV, than the pipe material. At the same time, the pipe hardened material extends to about 0,4 mm depth from external surface showing values up to 500 HV, higher than 300 HV average beyond 0,5 mm depth and 250 HV beyond 1,0 mm depth.

As a consequence, the deep crack from pipe surface with high hardness to about 2,25 mm depth, extended down to material where hardness is lower and there is no evidence of microstructural alteration.



# Main outcome

At the end of the three projects, main outcomes are:

- Cracks may be present since damage creation or initiate and develop at a later time. Depending on the tooth geometry, excavator size and coating, cracks may have different geometry and size;
- In the cracks area, the pipe material exhibits microstructural alteration and hardening, due to the damaging process. The pipe altered material is harder than the base material (500 HV vs 200 – 300 HV in the base material) and the tooth material is harder (≥ 600 HV);
- Coating (3 LPE) may act as a sort of lubricant between excavator tooth and pipe surface, so to reduce aggressivity of damages. In some cases, a thin layer of melted coating may still act as a protection of the damaged area and prevent crack formation. Nevertheless, in most cases of the present study, the coating was removed by the impacting tooth;
- Some cracks are branched, other have sharp edges, but in both cases with no plastic deformation. Such characteristics are attributable to the effect of hydrogen from cathodic over protection, especially if cracks grow deeper than the pipe hardened material;
- Genrally, cathodic over protection potentials (-1450 mV vs Cu/CuSO4) cause higher number of cracks with respect to standard cathodic protection potentials (-850 mV and -1150 mV vs Cu/CuSO4), where no evidence of cathodic protection detrimental effect was found;
- Cracks may grow with high R values ($P_{min}$ / $P_{max}$ = 0,9) of pressure cycling, representative of gas pipelines;
- The deepest cracks detected range from 1,75 mm to about 2,25 mm (from pipe external surface), that is 10 - 12,5% of the pipe wall thickness, to be added to the thickness reduction due to the gouge. In such a case, the total depth is up to 3,85 mm, that is about 22% of the pipe wall thickness;
- Basing on the size of the deepest crack, the highest estimated crack growth rate is approximately 0,31 µm/cycle.

# Conclusions

In conclusion:

- Cracks on third party damaged pipes under cathodic protection may be found even when considering modern pipe, not high grade, compliant to ISO 3183;
- Cracks start from the hard material on the pipe surface (tooth material or hardened pipe material), can initiate at the moment of damage creation or at a later time;
- Hence, in case of evidence of third party damage, the hardened material should be removed to prevent crack growth or initiation;
- Cracks grow or initiate especially at cathodic over protection potentials (-1450 mV vs Cu/$CuSO_4$), while at lower potentials (up to -1150 vs Cu/$CuSO_4$) there is no evidence of growth or initiation.
- When cathodic over protection is present, the crack growth rate may reach 0,31 µm/cycle at the testing conditions applied (UF = 72% SMYS and R = 0,9, representative of gas pipelines service conditions), and the cracks may extend to 10 – 12% of the pipe wall thickness inside the pipe base material. As a consequence, the total damage depth, crack and gouge, may be more than 20% of the pipe wall thickness and potentially affect the pipe resistance to internal pressure.

Thank you for your attention.