POLITECNICO DI MILANO





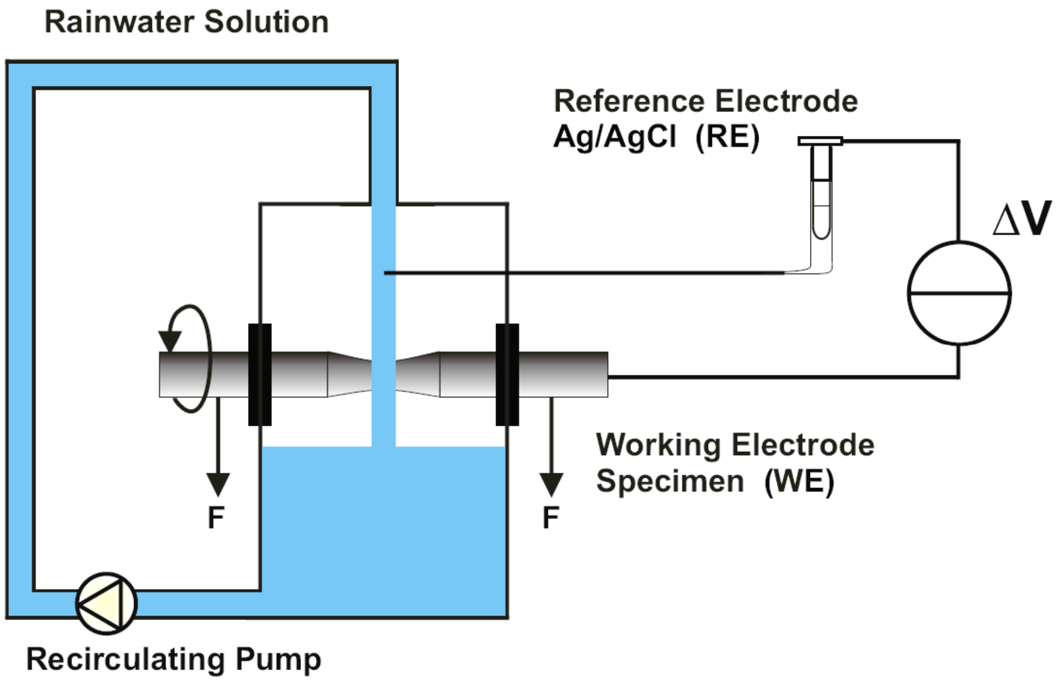
Development of models for life prediction under corrosion-fatigue

S. BERETTA, A. LOCONTE

Politecnico di Milano, Department of Mechanical Engineering

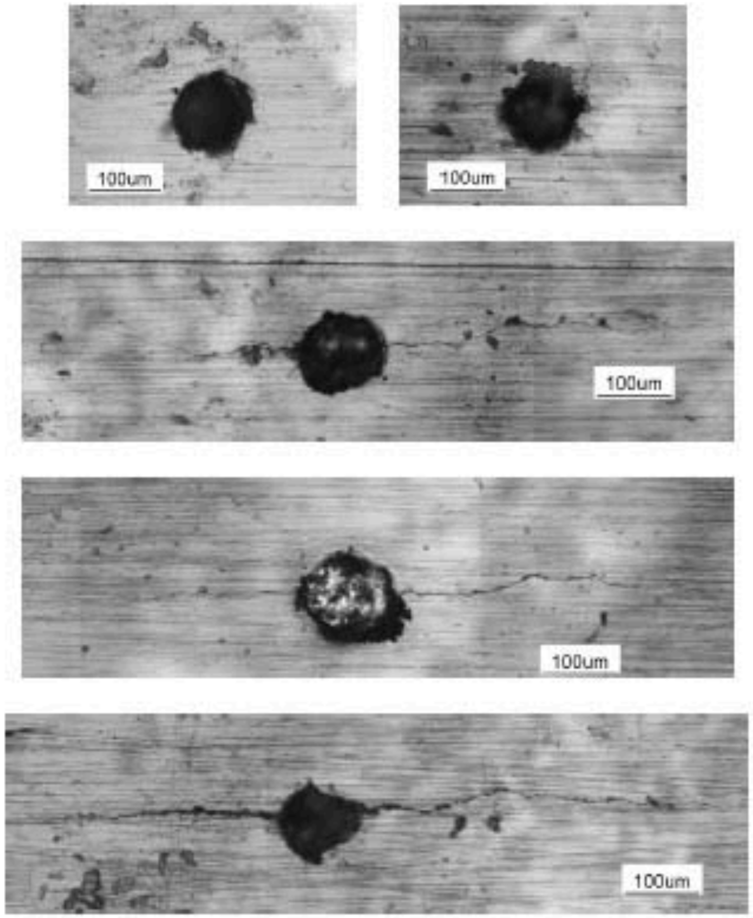
Research developed within WOLAXIM – EU Project

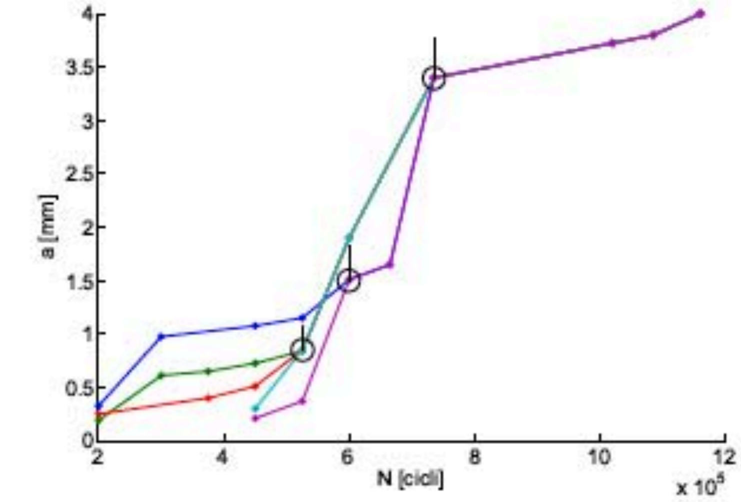
New test arrangement

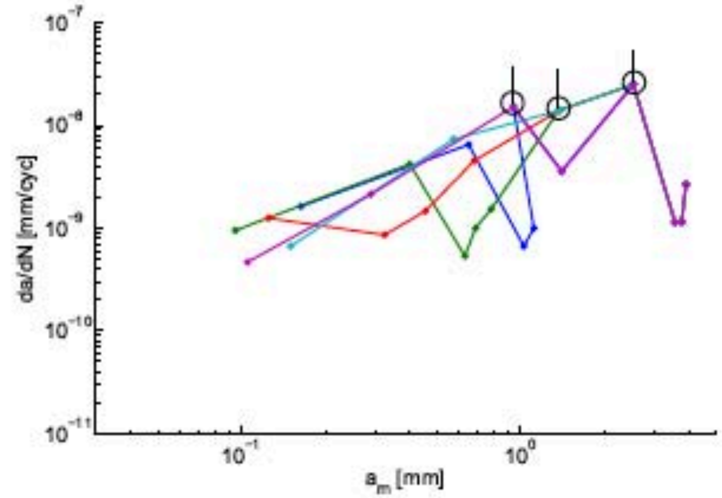


- tests with continuous dropping in order to measure corrosion potential;
- crack growth rate with plastic replicas;
- Confirmation of $\Delta K_{p\text{-}t\text{-}c}$ estimate;
- crack growth model under corrosive environment.

Crack growth rate measurements







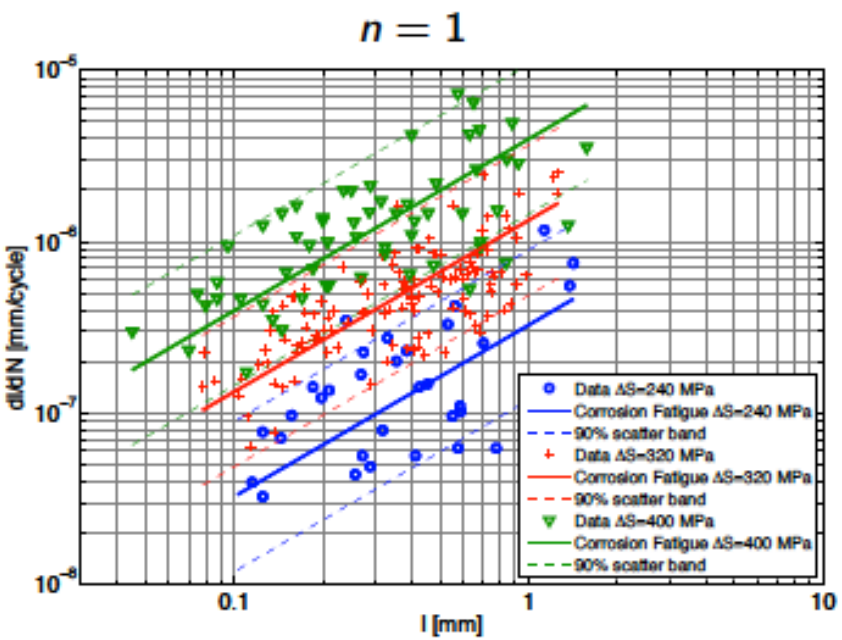
Simplification of the model

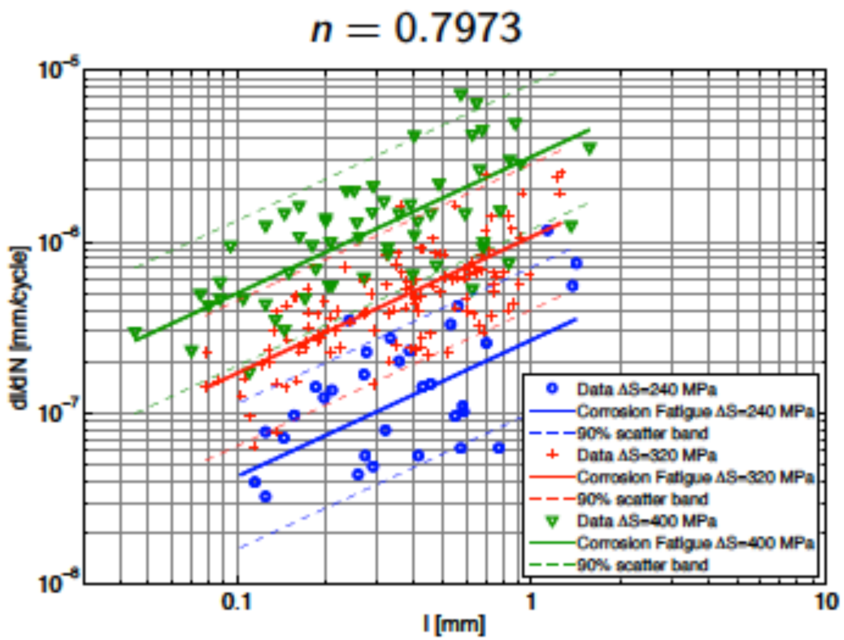
Modification of the Murtaza-Akid model into:

$$\frac{dl}{dN} = B \cdot (\Delta S)^{\beta} \cdot l - D$$

Further simplification:

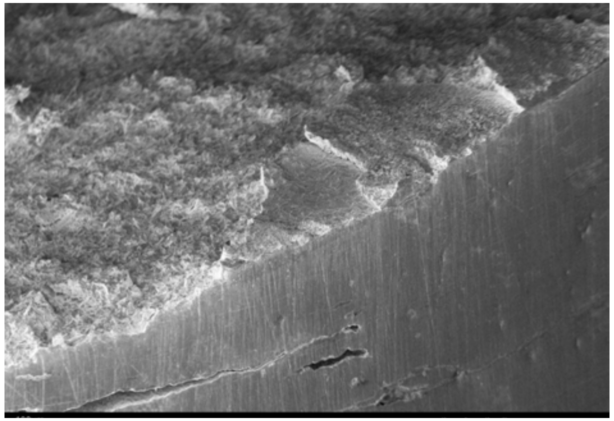
$$\frac{dl}{dN} = B \cdot (\Delta S)^{\beta} \cdot l^{n}$$



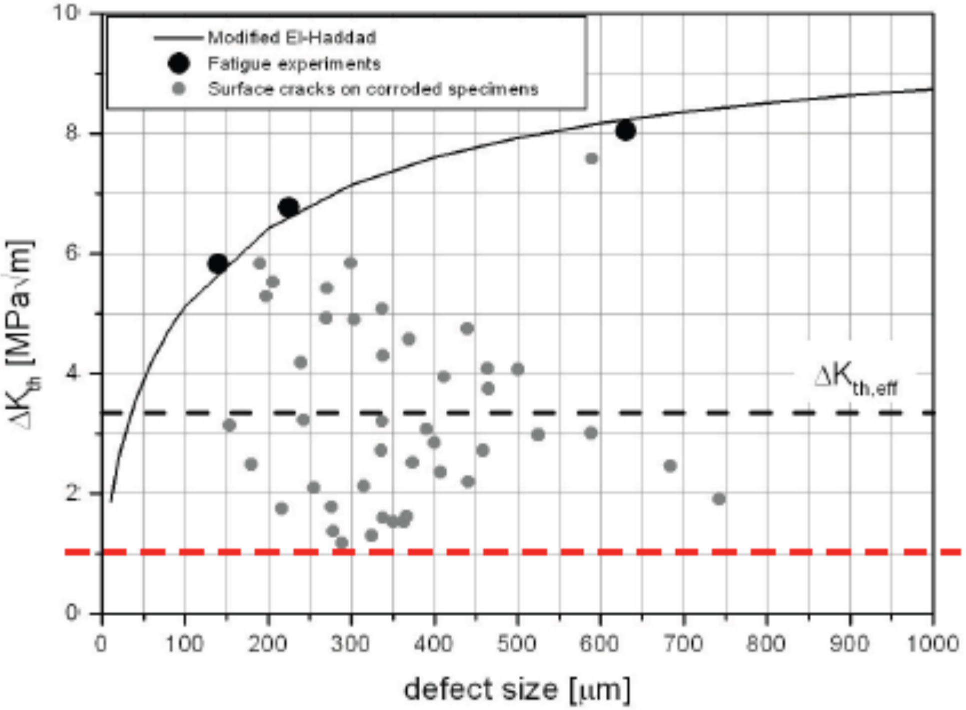


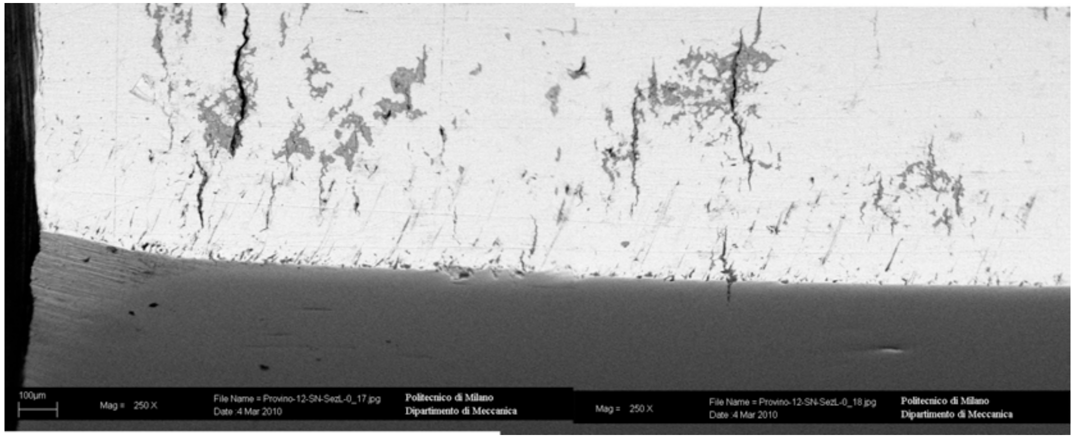
1) S. Beretta *, M. Carboni, G. Fiore, A. Lo Conte (2010)
Corrosion–fatigue of A1N railway axle steel exposed to rainwater. *Int. J. Fatigue*, 32 (2010) 952–961
2) S. Beretta, S. Gianellini (2010)
Discussion of a short crack growth model.., Prof. ECF18 Conference

Open point : crack formation process ?



- Cracks are able to propagate below ΔK_{th} because of the environmental effect





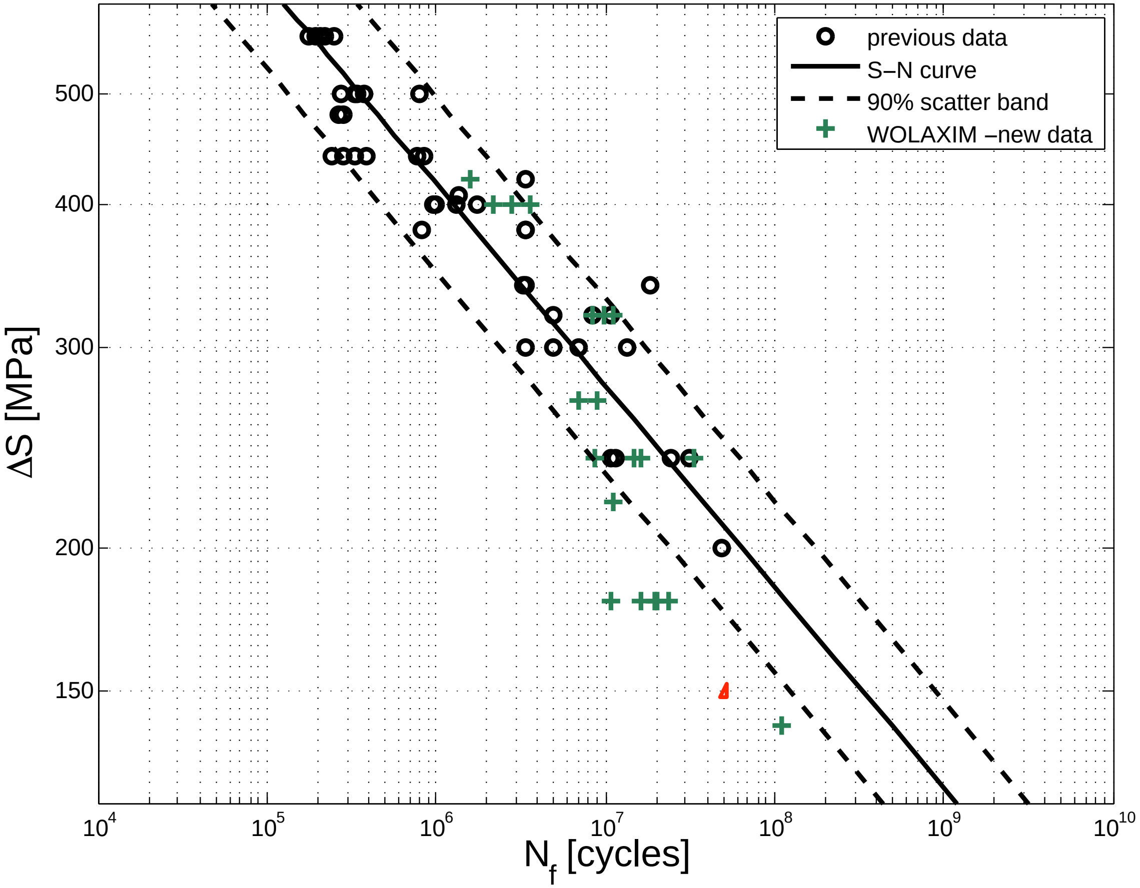
- Pit → crack ?
- How much this process can influence the life prediction ?

Outline of the research

- Corrosion-fatigue model for A1N
  1. Consolidation of S-N diagram at very high number of cycles;
  2. Interrupted tests with surface analysis for detecting pit evolution;
  3. Refinement of life prediction model;
- Development of a similar model for A4T;
- Surface damage as a ‘fatigue indicator’ and development of a new detection device (TWI);

Corrosion-fatigue model for A1N

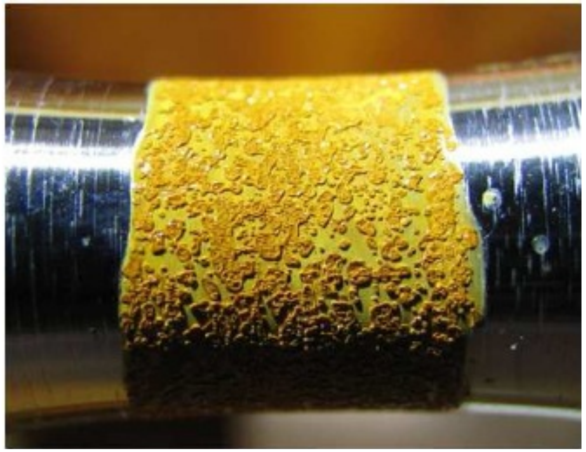
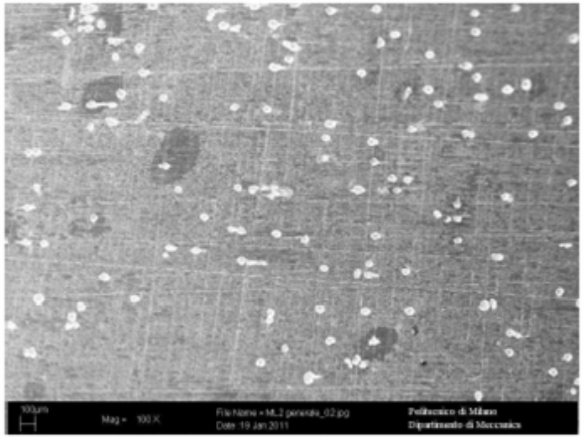
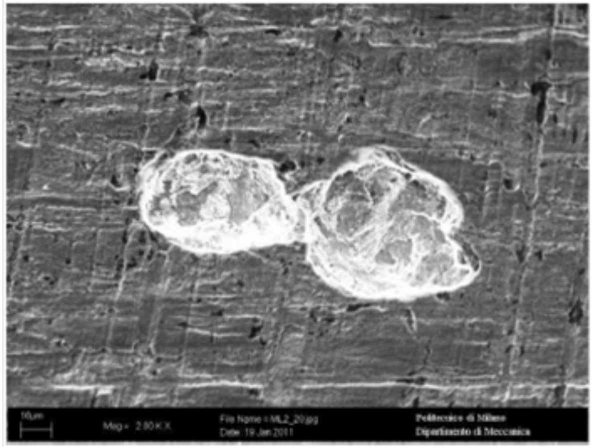
SN diagram



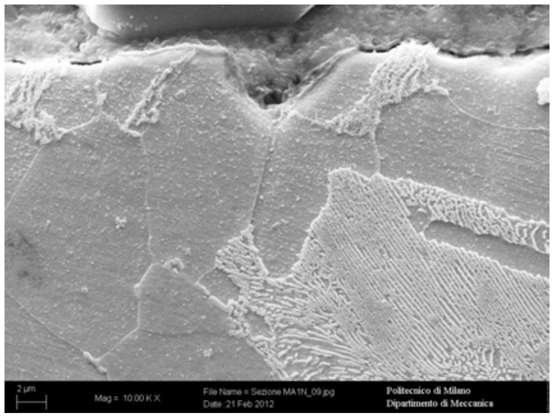
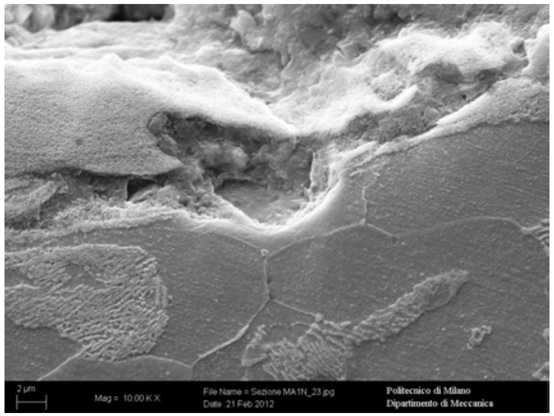
- Careful repeated experiments (8 hz) for consolidating S-N diagram at low stress amplitudes: longest test approx. 9 months;
- Interrupted tests for observing damage evolution

Early stage of the corrosion fatigue process

- 1st: SEM observation of the specimens
- 2nd: sectioning of the specimens

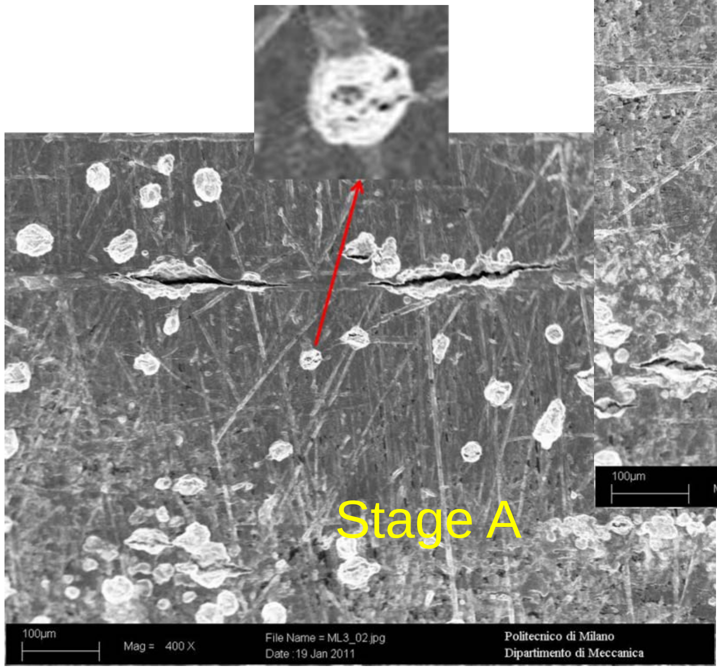
Detail of corrosion pits onto the surface of the ML2 specimens $\Delta\sigma$=400 MPa *interrupted at 1 10*^{5}*).*

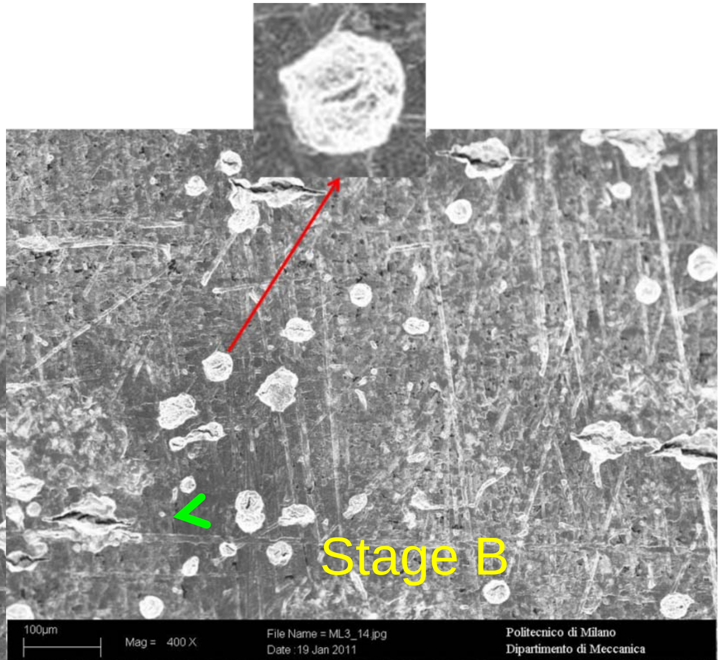



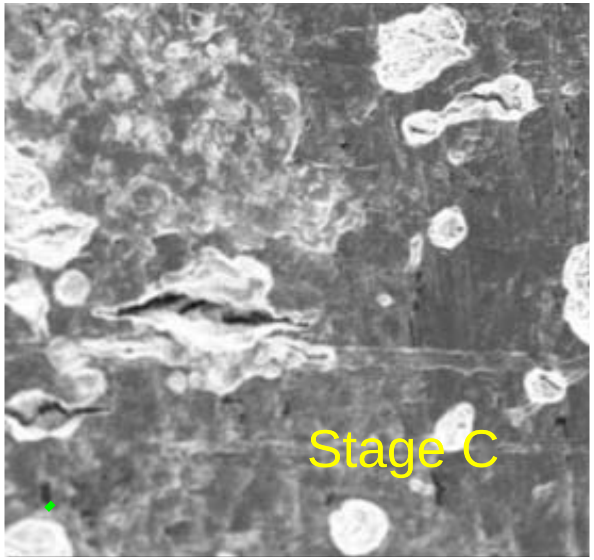
- Corrosion pits start in ferrite grains

Pit-to-crack evolution

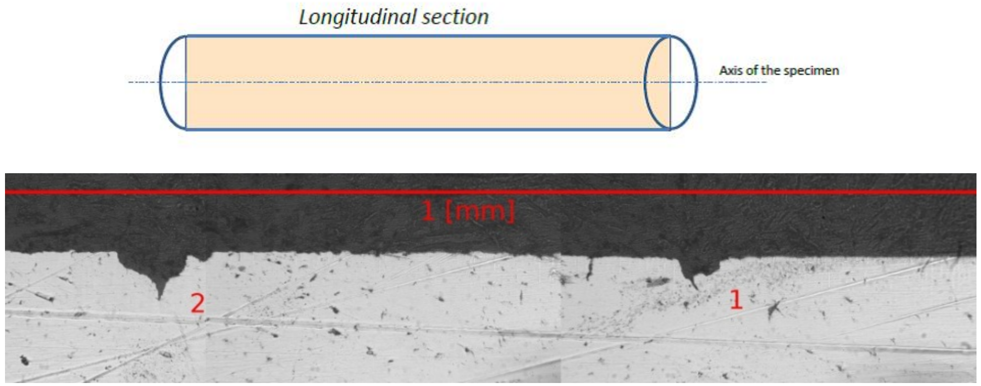
- Stage A: primary pit plus secondary pit
- Stage B: small crack at the bottom of the primary pit
- Stage C: propagation of the microcrack out of the pit

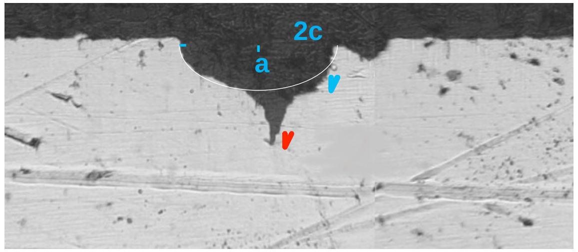






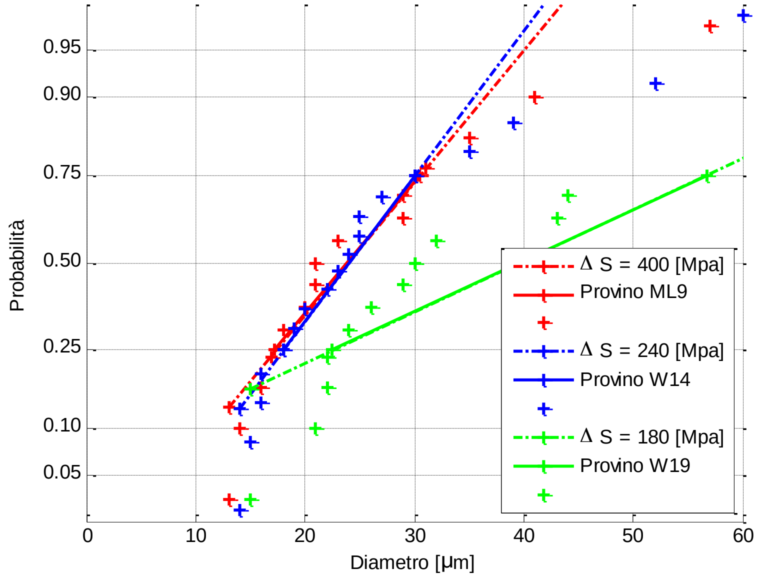
Crack growth mechanism

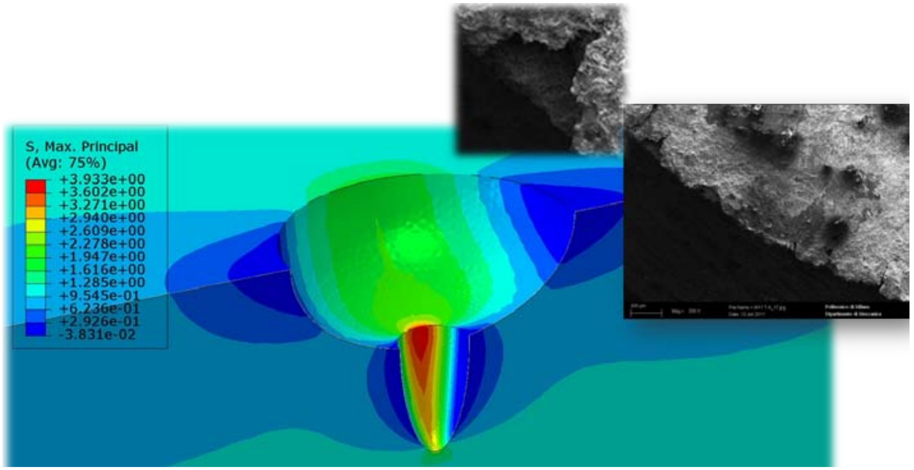




- Aspect Ratio primary pit: ≈ 0.4
- Aspect Ratio secondary pit: ≈ 1.6

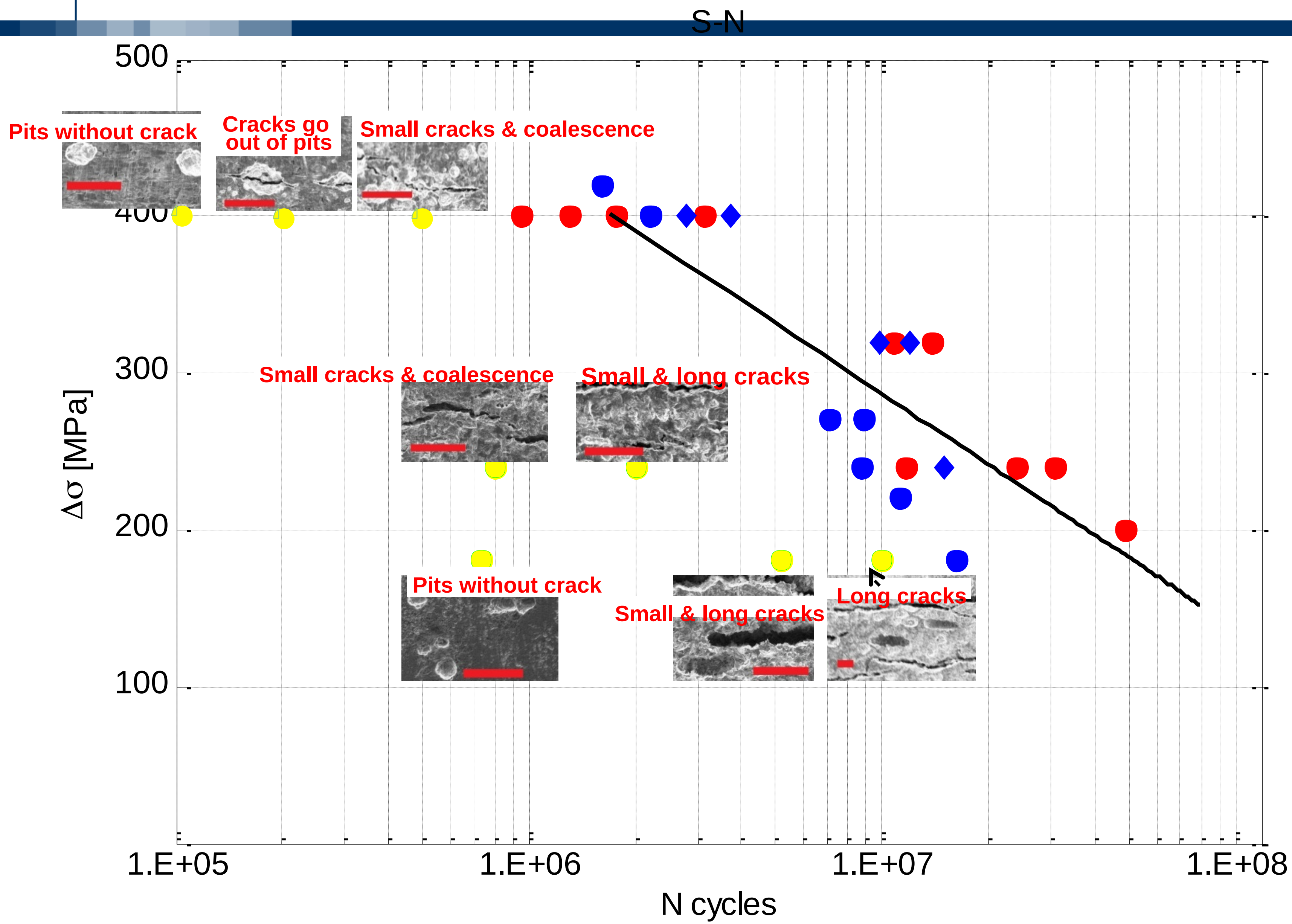
Diameter of the pit at the transition





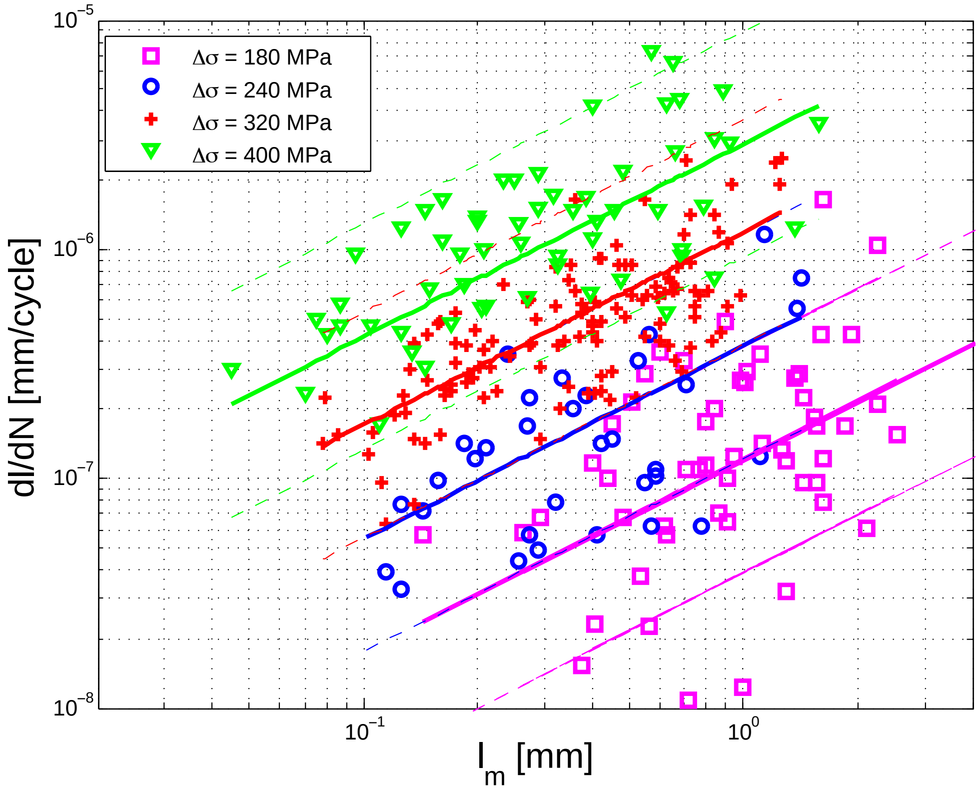
$K_{p\text{-}t\text{-}c} = 0.7\text{-}1.4\ \text{MPa}\sqrt{m}$

Damage evolution at different stresses



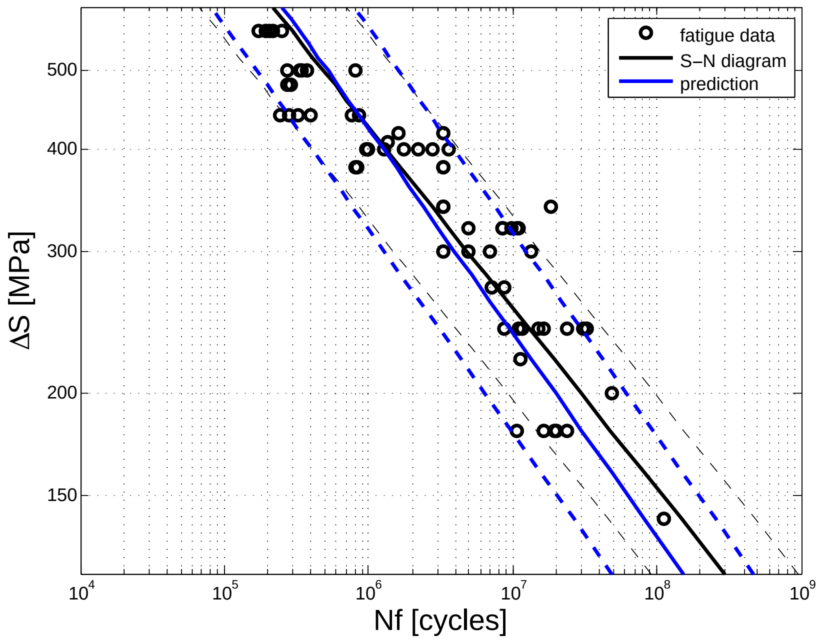
Crack growth model for A1N

- Addition of crack growth data at ΔS=180 MPa confirm the same type of model;
- Flattening of crack growth data for l > 1 mm ?

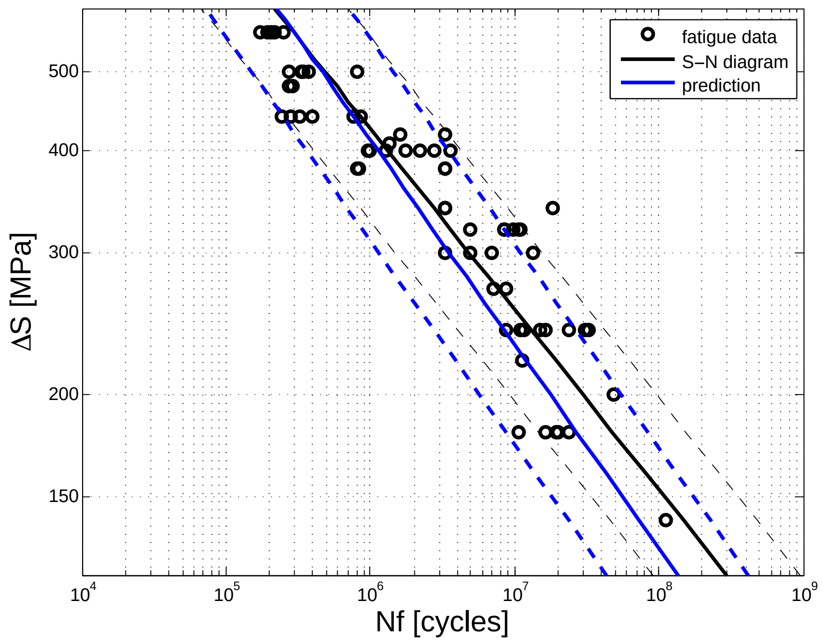


Prediction

l_o = 20 μm



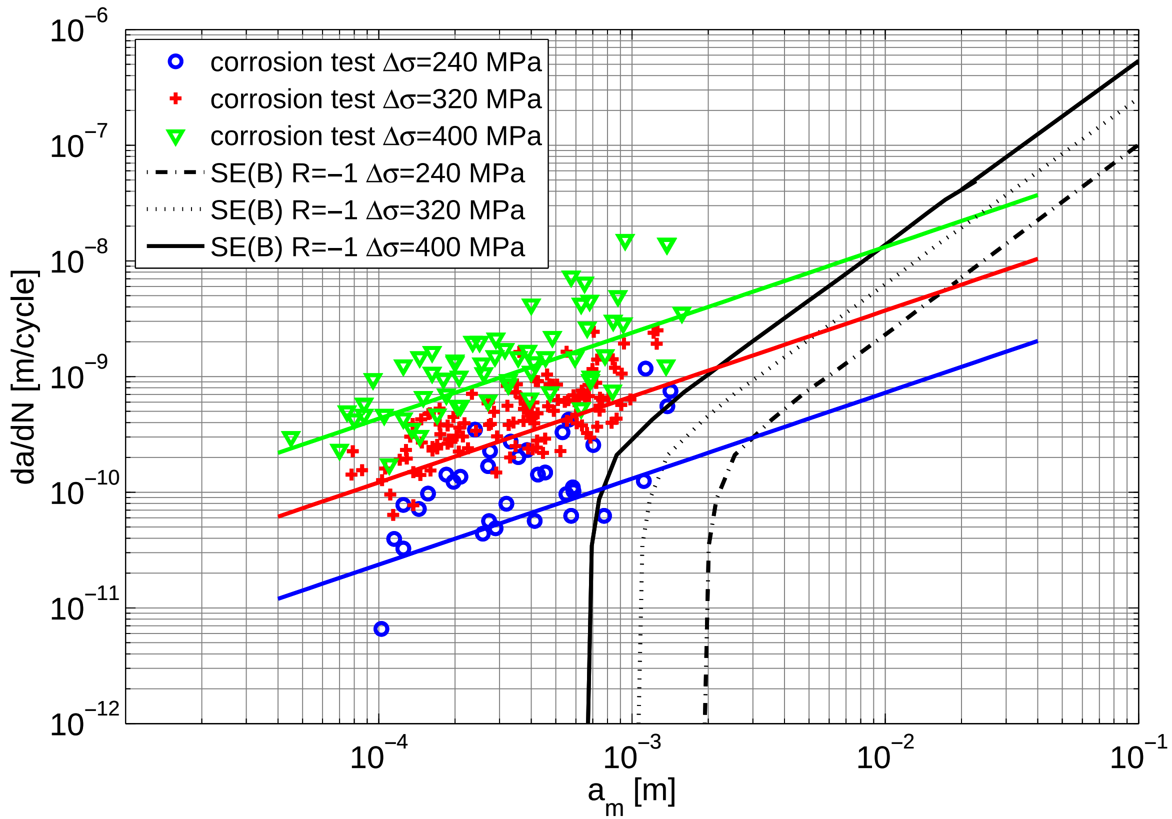
l_o = 40 μm



- Pit-to-crack transition occurs approx. at 5-10% ;
- Life estimation is very good (scatter also);
- Probabilistic model being incorporated into STRUREL Software (RCP, Germany)

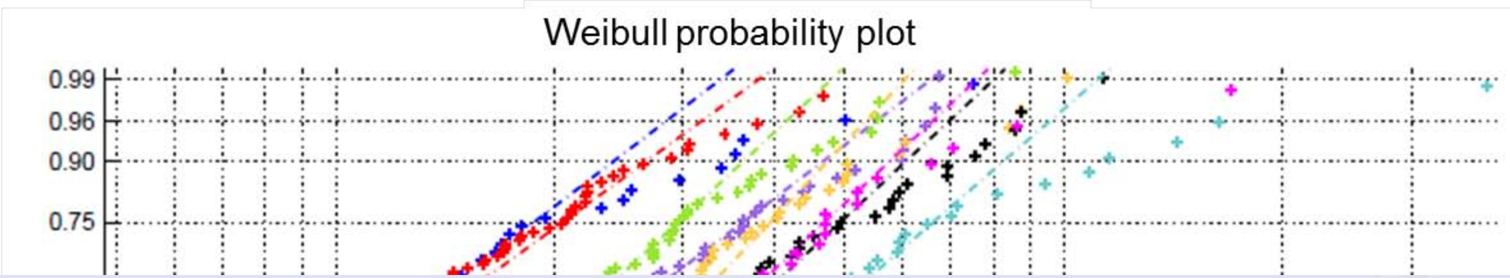
Competition with crack growth in air

If we compared the corrosion-fatigue growth rate with simple ‘in air’ crack growth rate

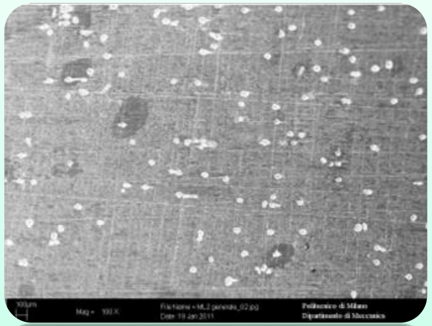


- from a surface length of 3-6 mm the propagation in air is more rapid !
- This phenomenon has to be considered for life estimation of an axle

Weibull probability chart for tests Δσ=400 MPa

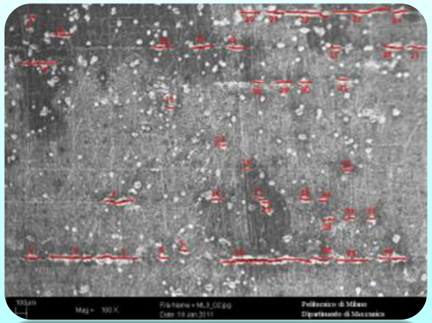


Stage 1


Test ML2 (10^5 cycles) (11%)

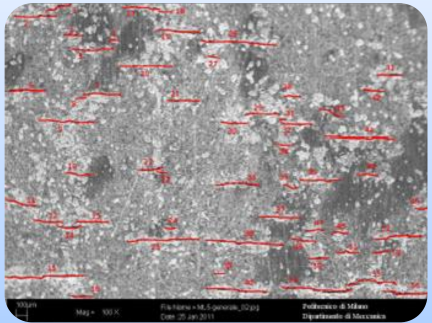
Pitting only

Stage 2


Test ML3 (2.10^5 cycles) (22%)

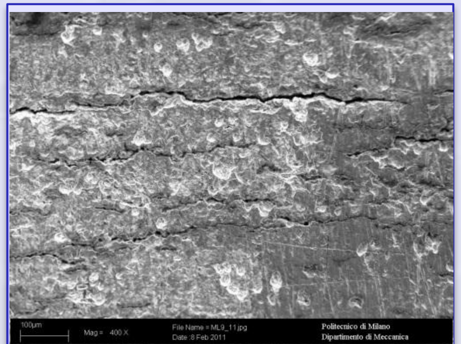
Formation of micro-cracks

Stage 3


Test ML5 (4.10^5 cycles) (44%)

Coalescence of micro-cracks (when depth exceeds 0.3mm)

Stage 4


Test ML9 ($8x10^6$ cycles)(88%)

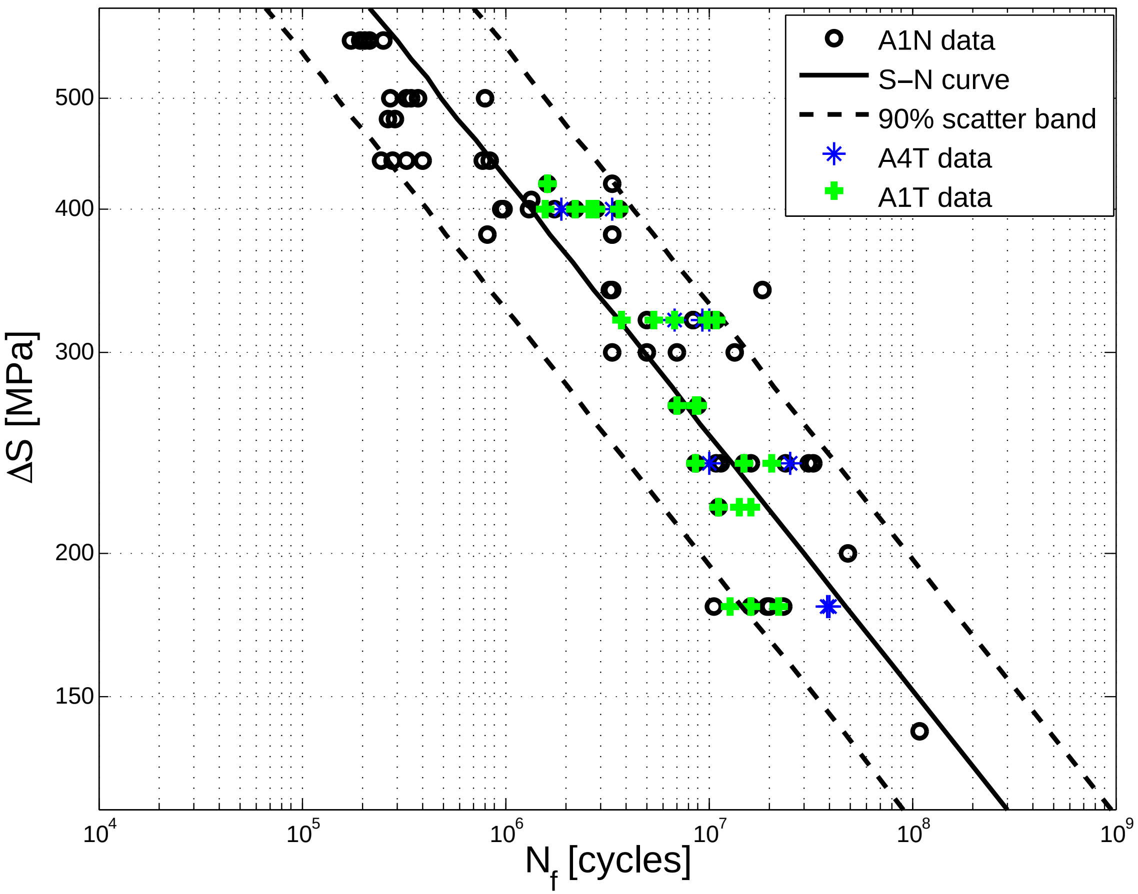
Growth of macro-cracks detectable by conventional NDT techniques

Idea: corrosion-fatigue detection in terms of surface cracking

New detection device

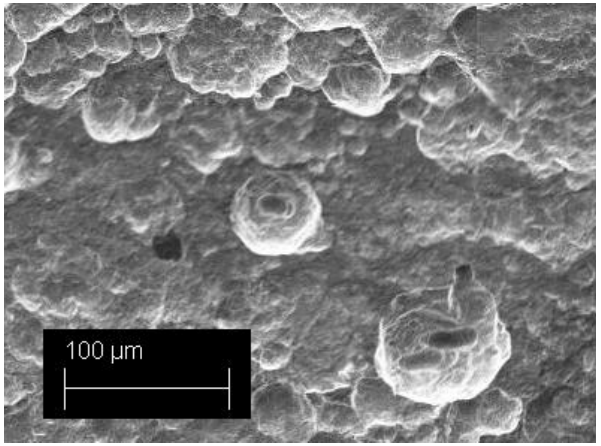
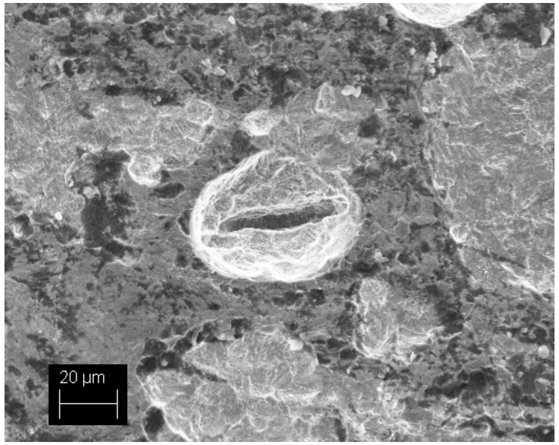
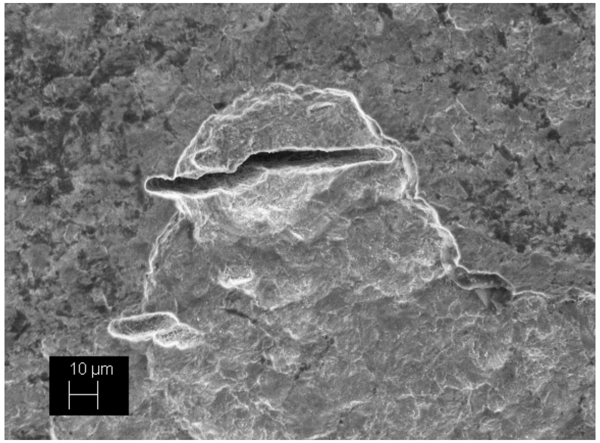
Corrosion-fatigue model for A4T

Different axle steels



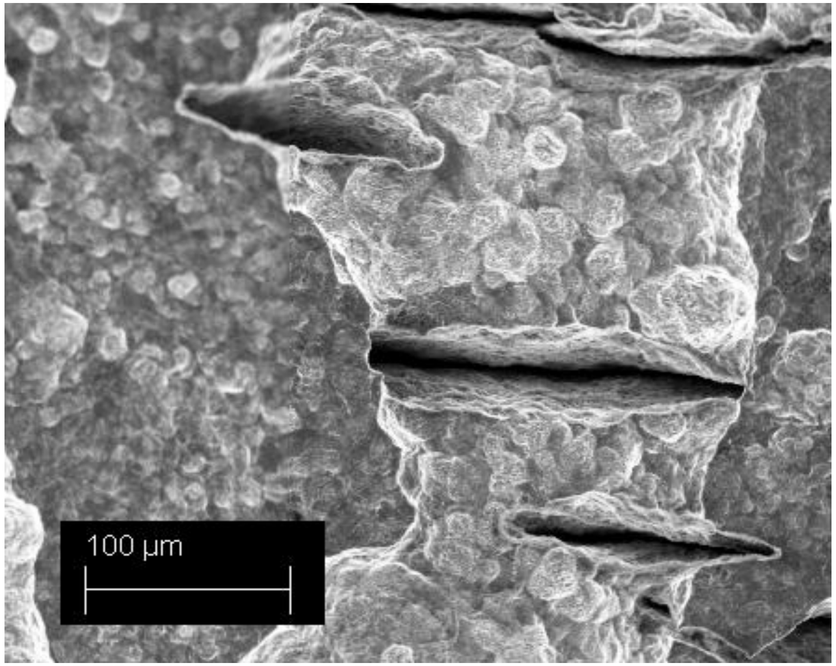
The same S-N diagram under corrosion-fatigue looks to describe the phenomenon for 3 different axle steels !

FIRST STAGE OF LIFE – PITTING CORROSION:

PIT TypeA	PIT TypeB	PIT TypeC
		
8E5cycles – 180MPa	8E5cycles – 240MPa	8E5cycles – 240MPa

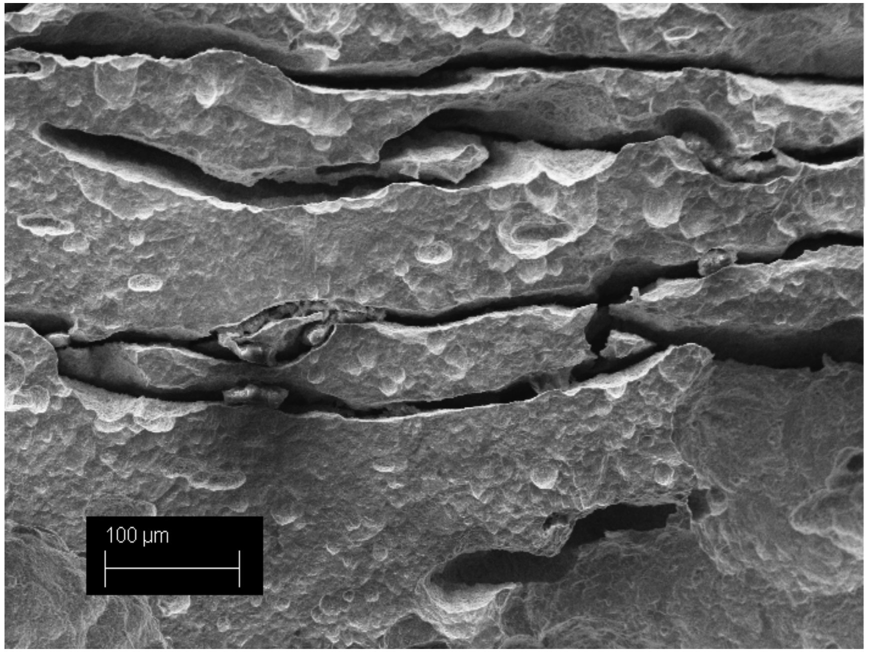
SECOND STAGE OF LIFE – CRACK DAMAGE:

SINGLE Cracks



6E6cycles – 180MPa

COALESCENCE

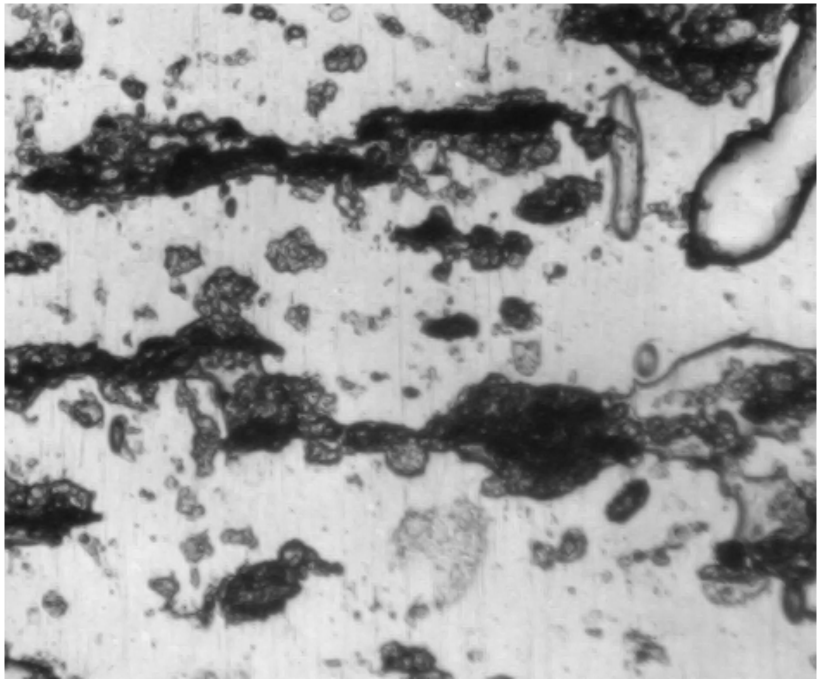


6E6cycles – 240MPa

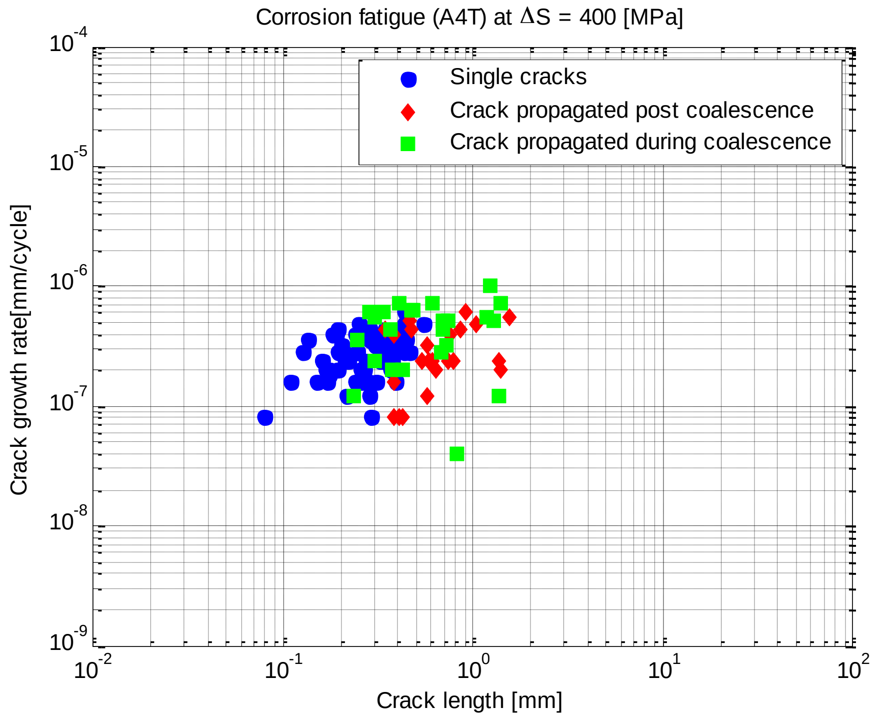
SMALL SCALE TEST

1. PROPAGATION TEST – PLASTIC REPLICAS:

with different measures on the same specimen it is possible to obtain the crack growth rate at different stress levels, but it is impossible to measure the density of the surface defects. Defects have to be bigger than 50-100 micrometers



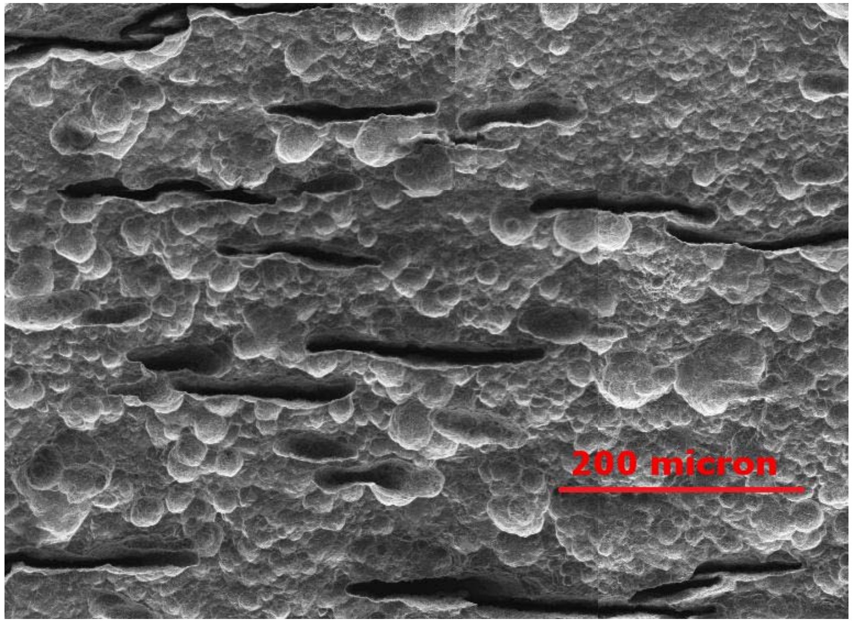
1E6cycles – 400 MPa



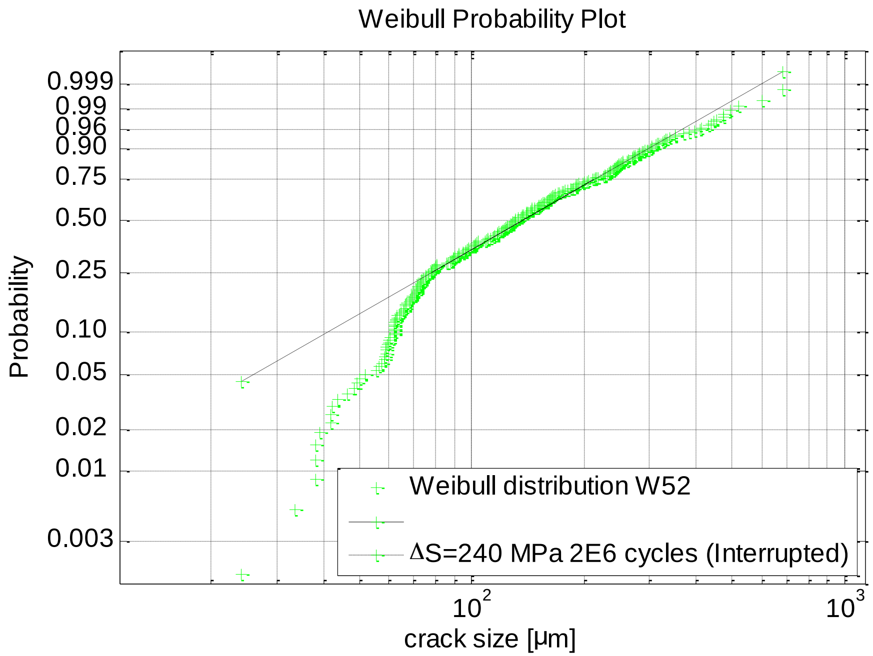
SMALL SCALE TESTS

1. INTERRUPTED TEST – PICKLING and S.E.M. ANALISYS:

with refined measures on different specimen it is possible to obtain the distribution of the surface defects, but it is impossible to obtain crack growth rate measures. It is possible to see defects smaller than 20 micrometers

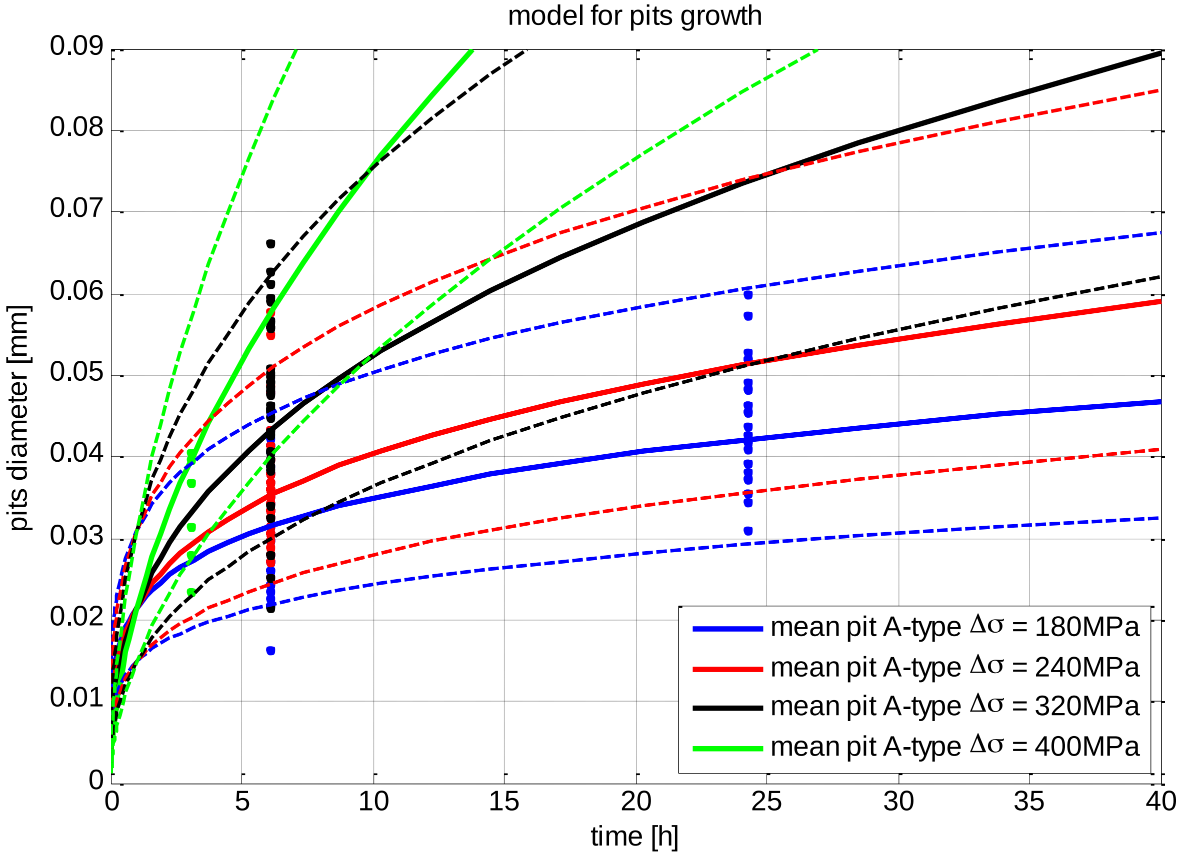


2E6 cycles – 240MPa



PIT MODEL

$$d = k \cdot t^q \qquad q = 10^{(l \cdot \sigma_a + b)}$$



SIMPLE GROWTH MODEL – 1

CRACK MODEL

$$\begin{cases} \frac{da}{dN} = B \cdot \Delta\sigma^{\beta} \cdot a^{n} & con \quad a \leq 0{,}6mm \\ \frac{da}{dN} = B \cdot \Delta\sigma^{\beta} \cdot 0{,}6^{n} & con \quad a > 0{,}6mm \end{cases}$$

da/dN = crack growth rate [mm/cycle]

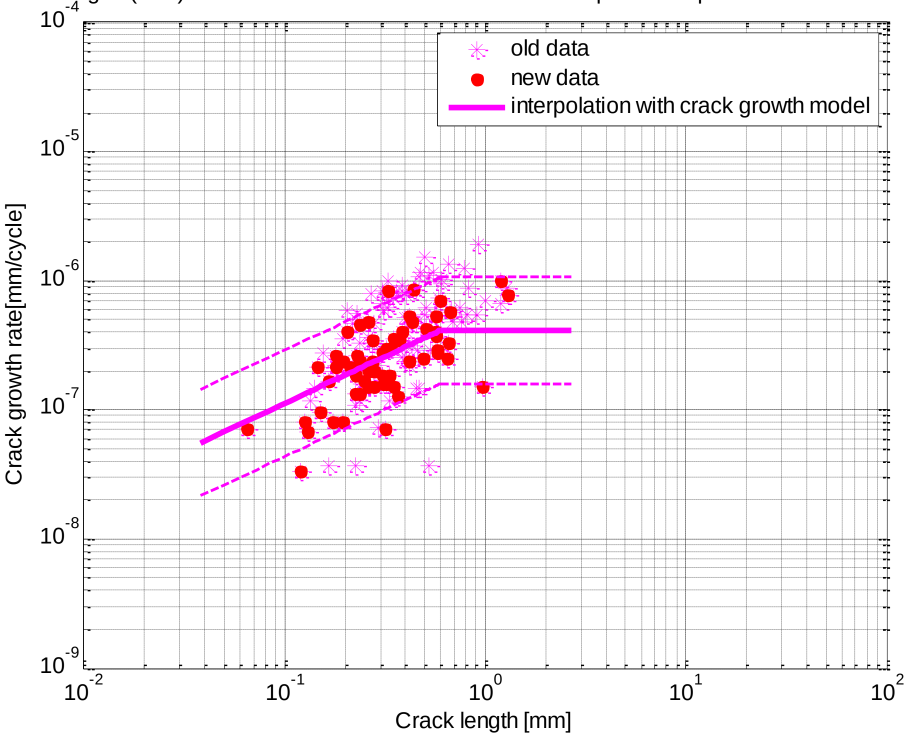
B, β, n = experimental constant to be find

a = crack length [mm]

N = number of cycles

$\Delta\sigma$ = amplitude of stress [MPa]

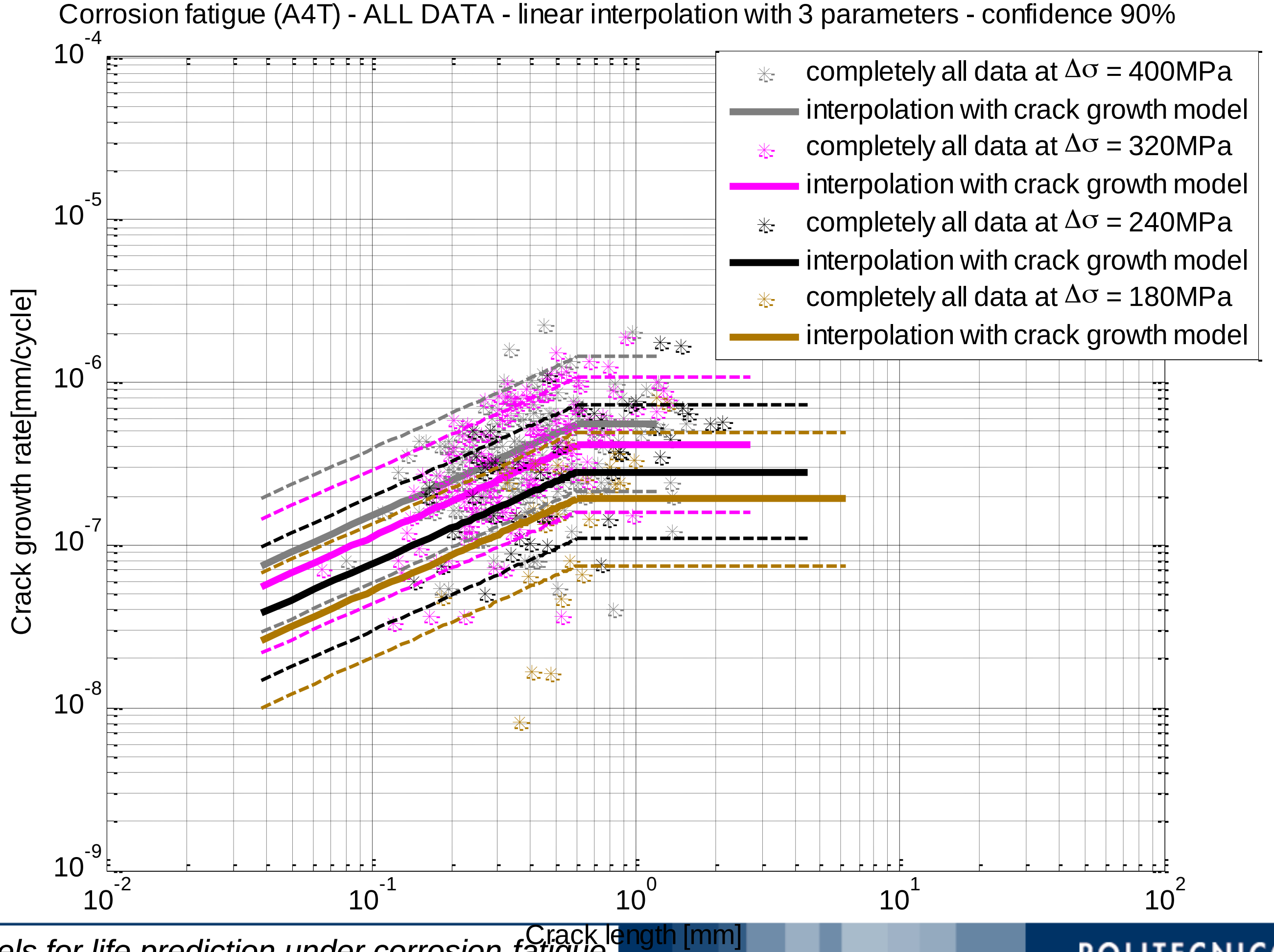
Corrosion fatigue (A4T) at Δσ = 320MPa - ALL DATA - linear interpolation 3 parameters - confidence 90%



SIMPLE GROWTH MODEL – 2

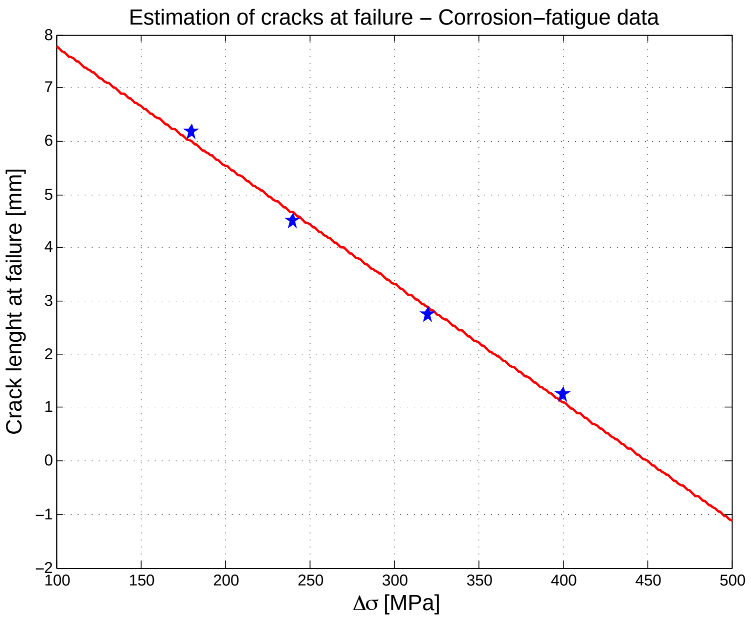
CRACK MODEL

$$\begin{cases} \dfrac{da}{dN} = B \cdot \Delta\sigma^{\beta} \cdot a^{n} & con \quad a \leq 0{,}6mm \\ \dfrac{da}{dN} = B \cdot \Delta\sigma^{\beta} \cdot 0{,}6^{n} & con \quad a > 0{,}6mm \end{cases}$$

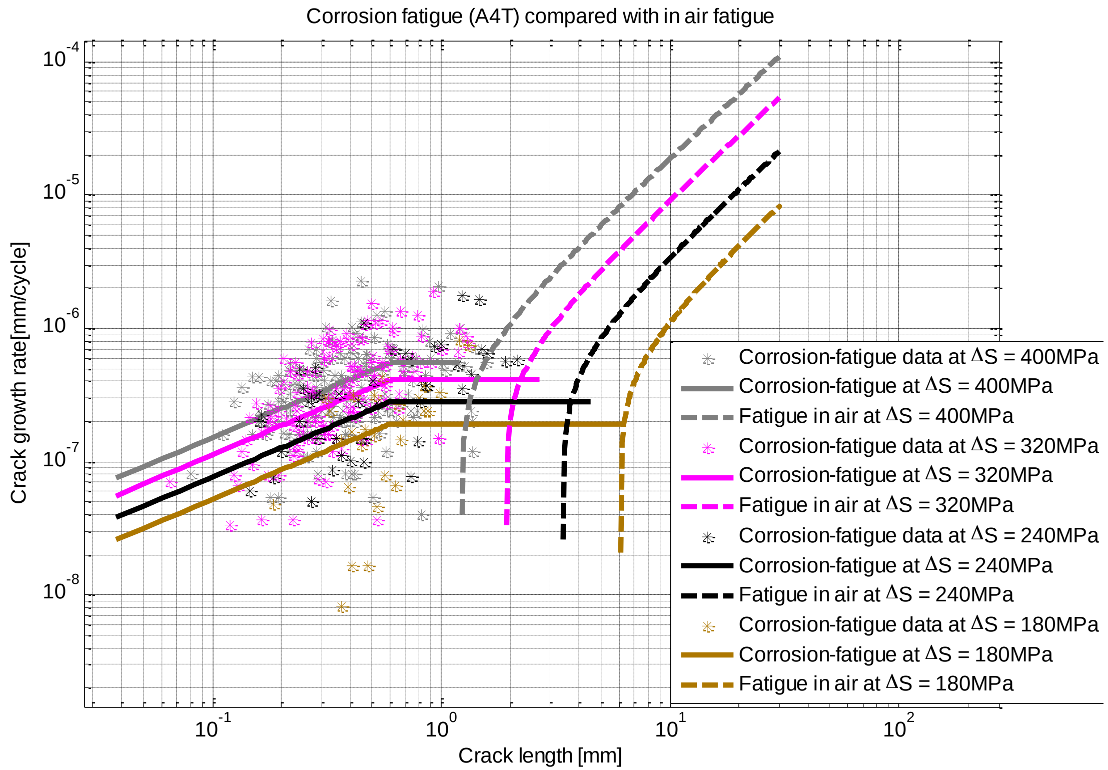


Cracks at failure

Estimation of max. crack at failure by ‘extreme value’ analysis (POT method)



Comparison of crack growth data → transition to ‘fatigue’ crack growth



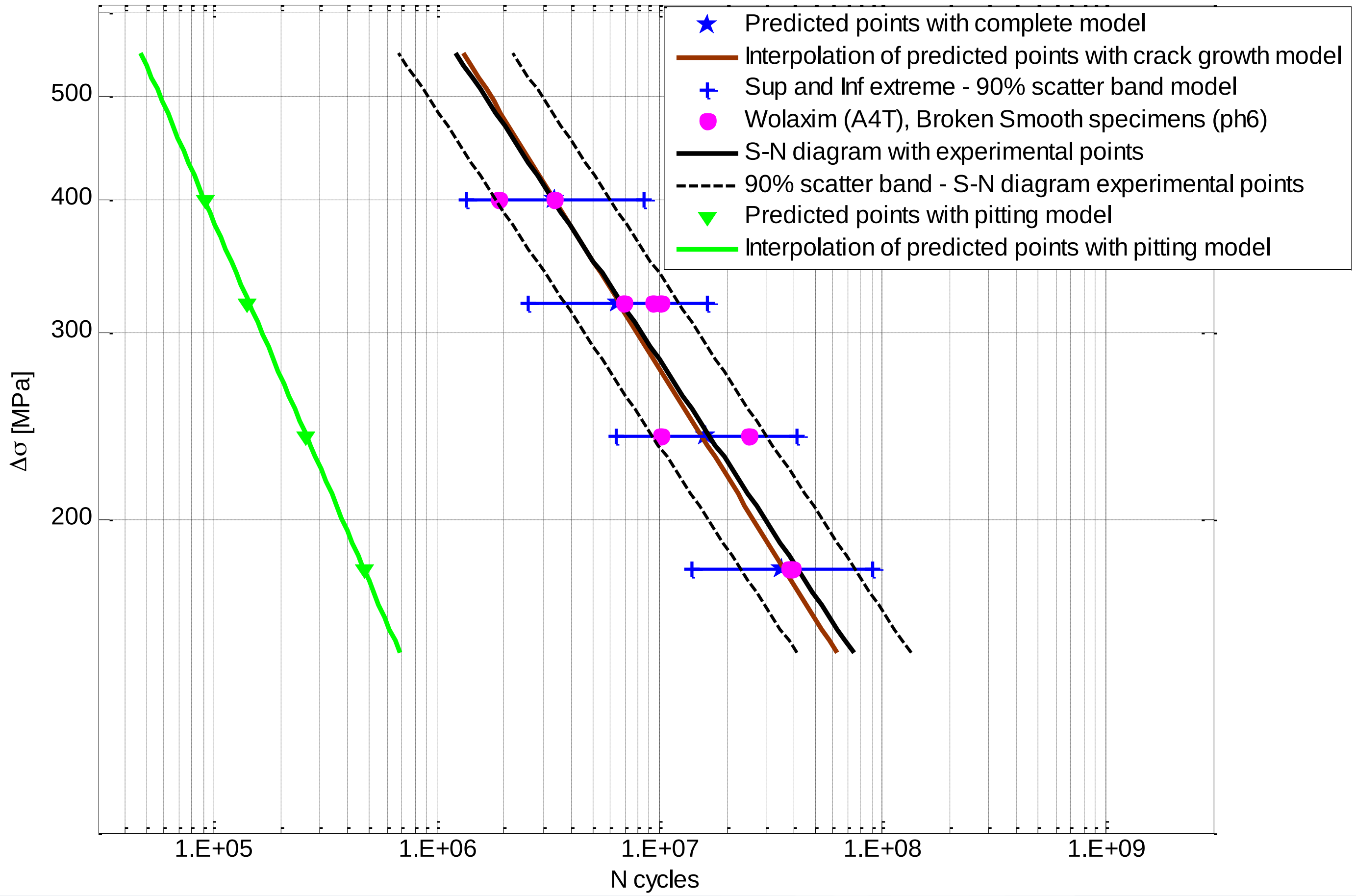
Max. crack at failure corresponds to the transition to a more rapid phenomenon

SIMPLE DAMAGE MODEL – PREDICTION OF THE SPECIMEN’S LIFE

Number of cycles at the break point for the 4 different stress level

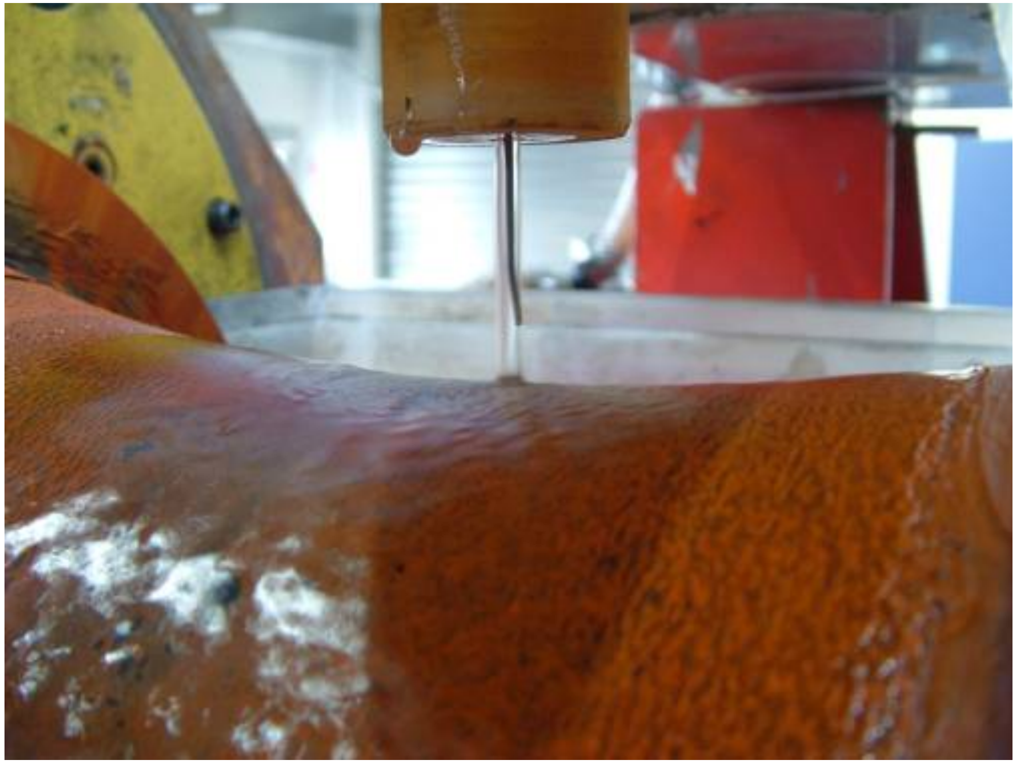
Included only the crack growth scatter

S-N - Simple damage model (with pits model) compare to experimental broken specimen

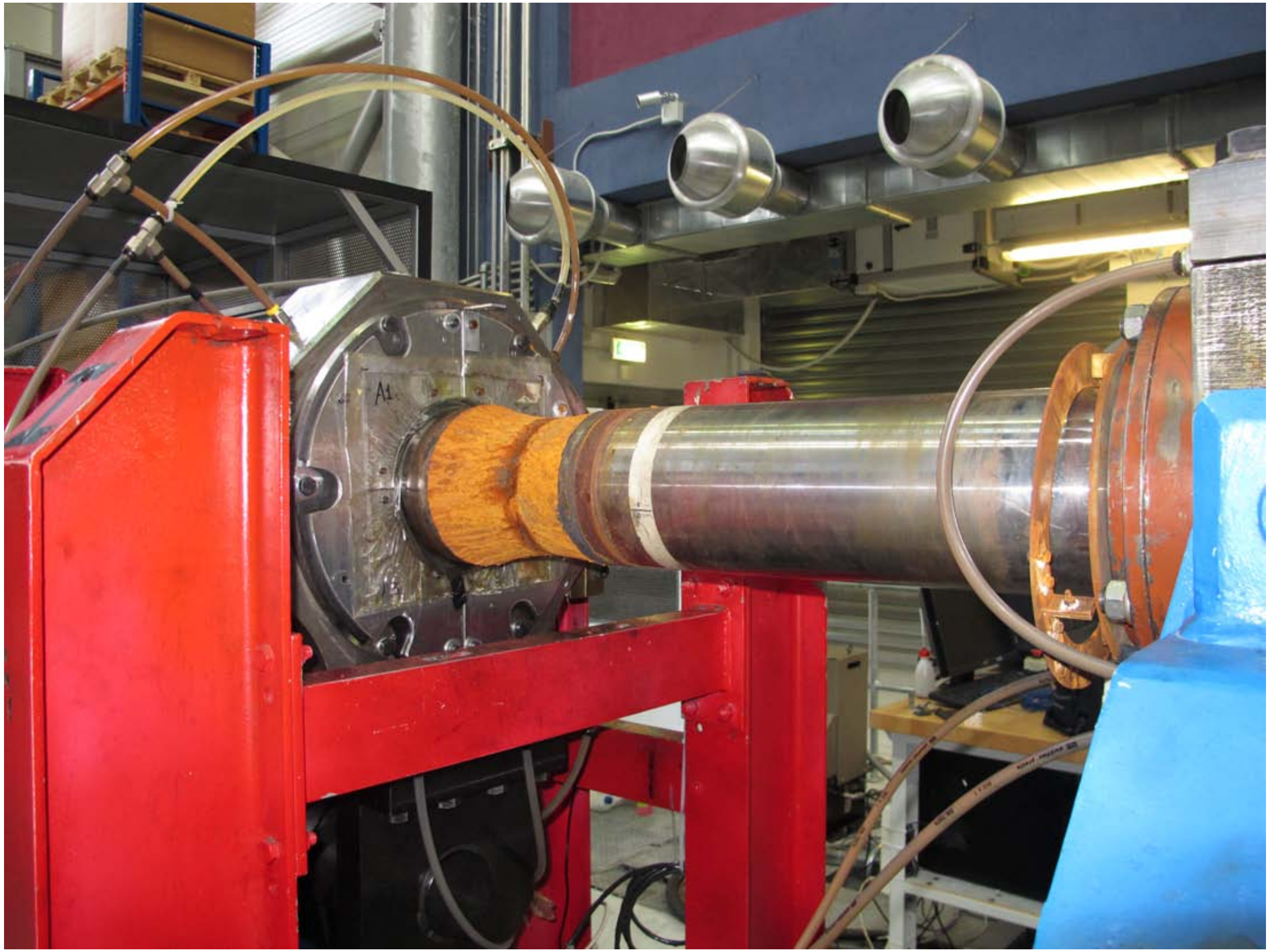


Full-scale corrosion-fatigue tests

- Full-scale experiments onto a 'Vitry type' bench: same setup of the small scale testing
- Tests on A4T (CA and VA) for model verification;



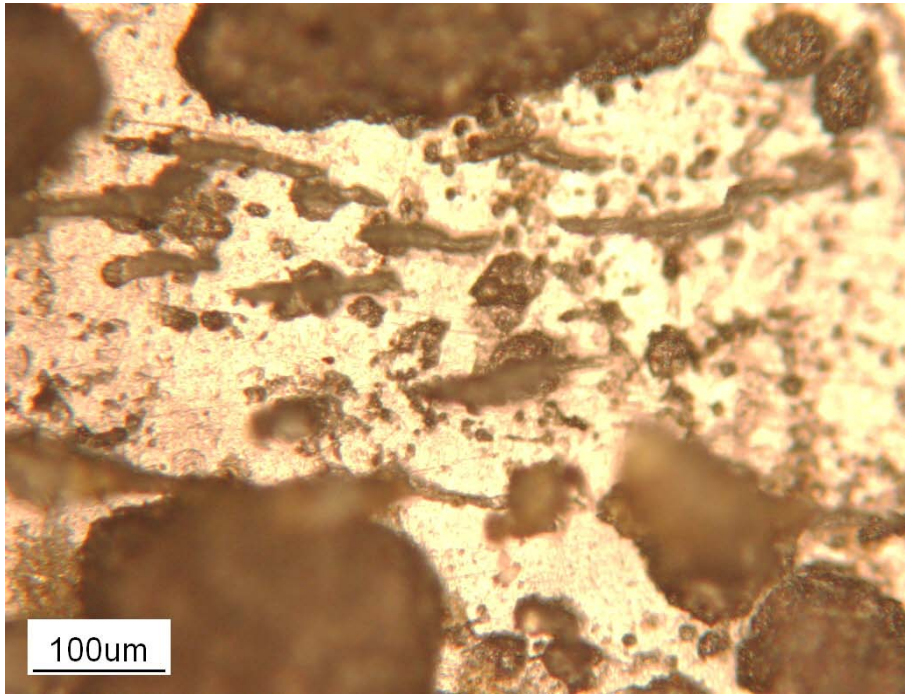
Full-scale tests



FULL SCALE TEST

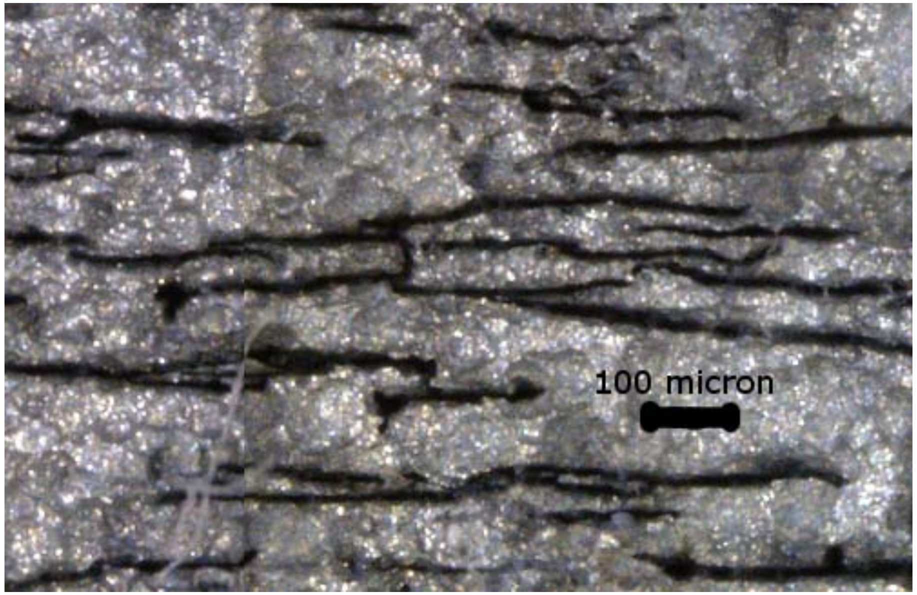
Inspection of the axle's surface in different stage of life using different inspection methods:

PLASTIC REPLICAS



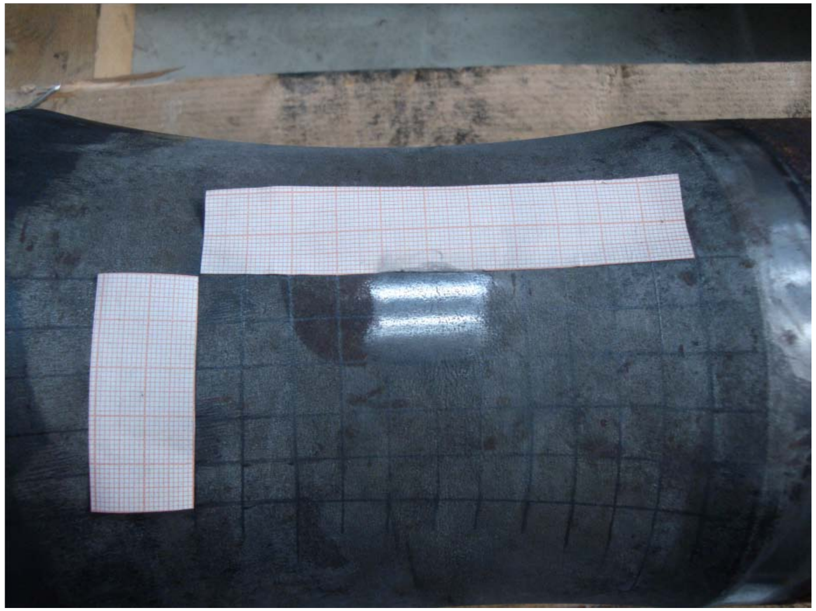
2E6 cycles – 240 MPa

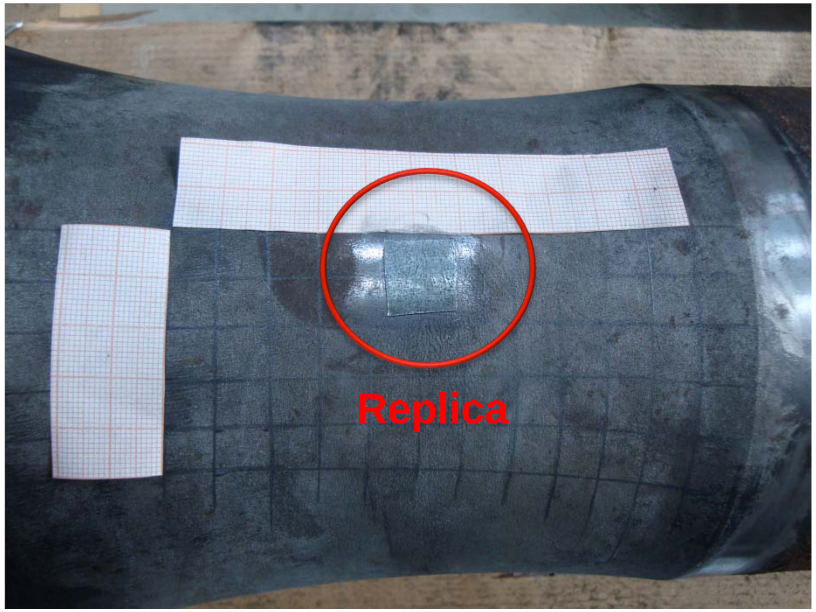
DIGITAL MICROSCOPE



12E6 cycles – 240 MPa

Mechanical cleaning– 4.317e6 cycles





After mechanical cleaning

Maximum crack a 4.317e6 cicli – 0deg

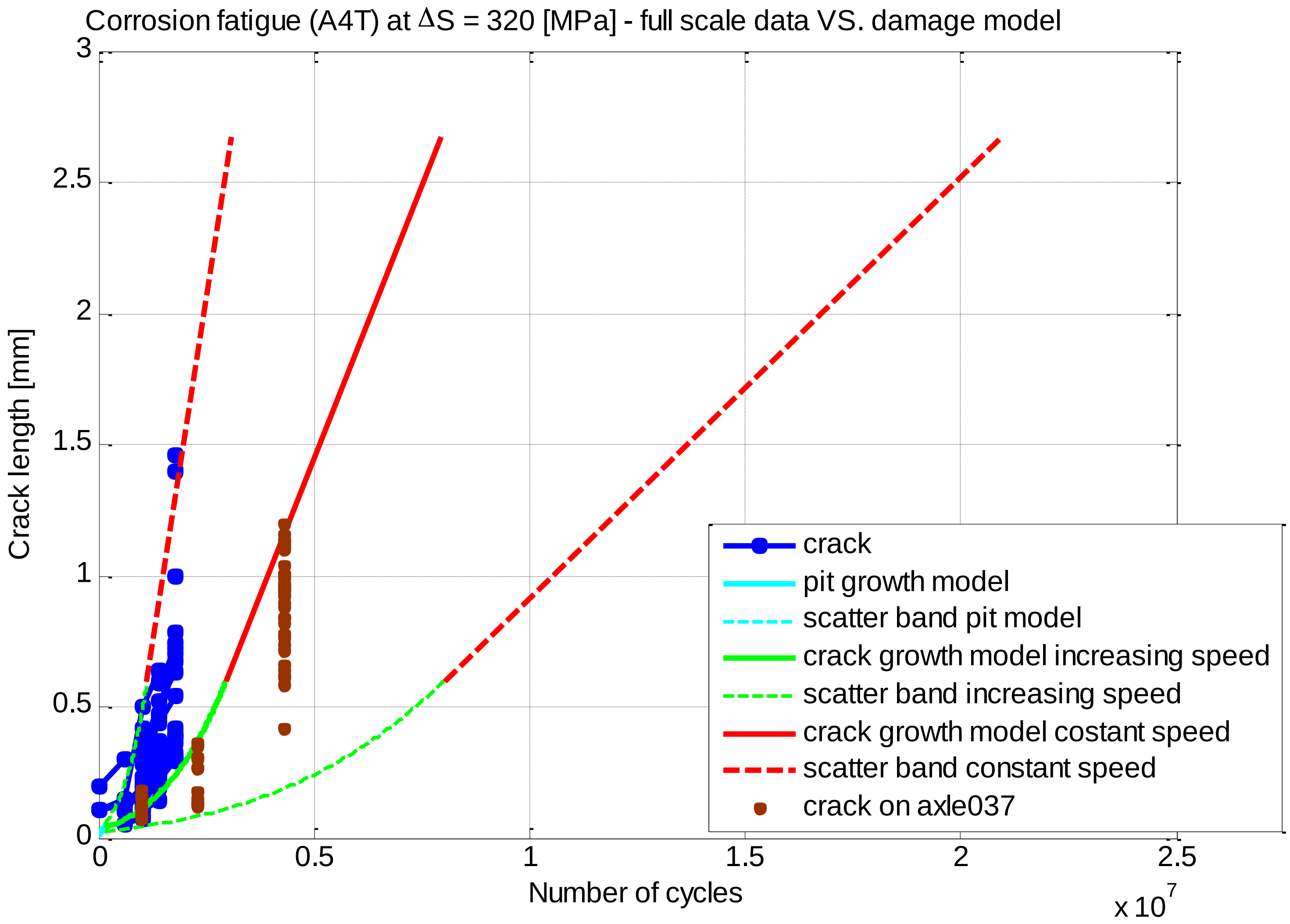
l = 1261 µm

TWI Optical device

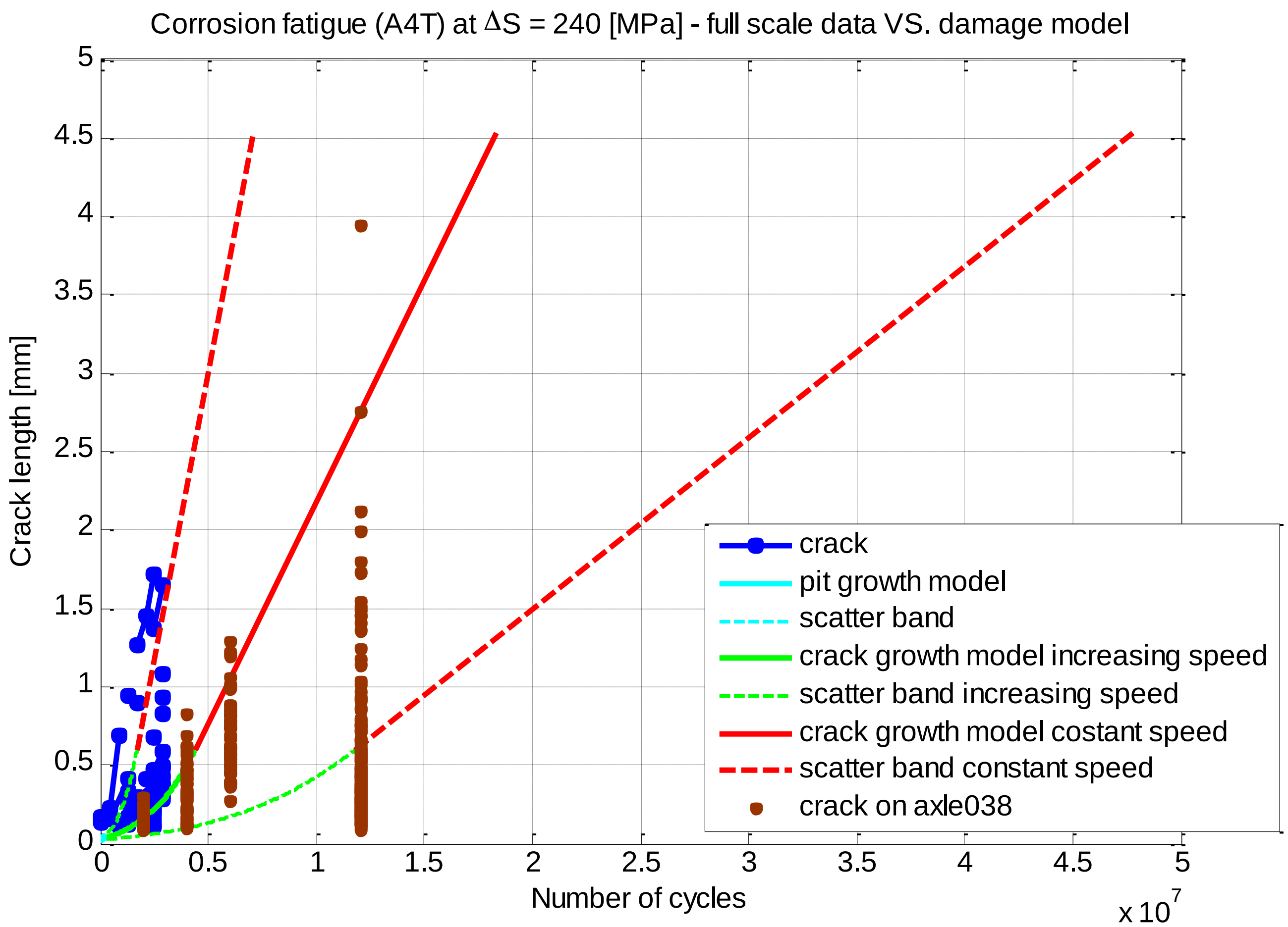
l = 980 µm

Plastic replica

FULL SCALE TEST – 1^ AXLE (160 MPa)

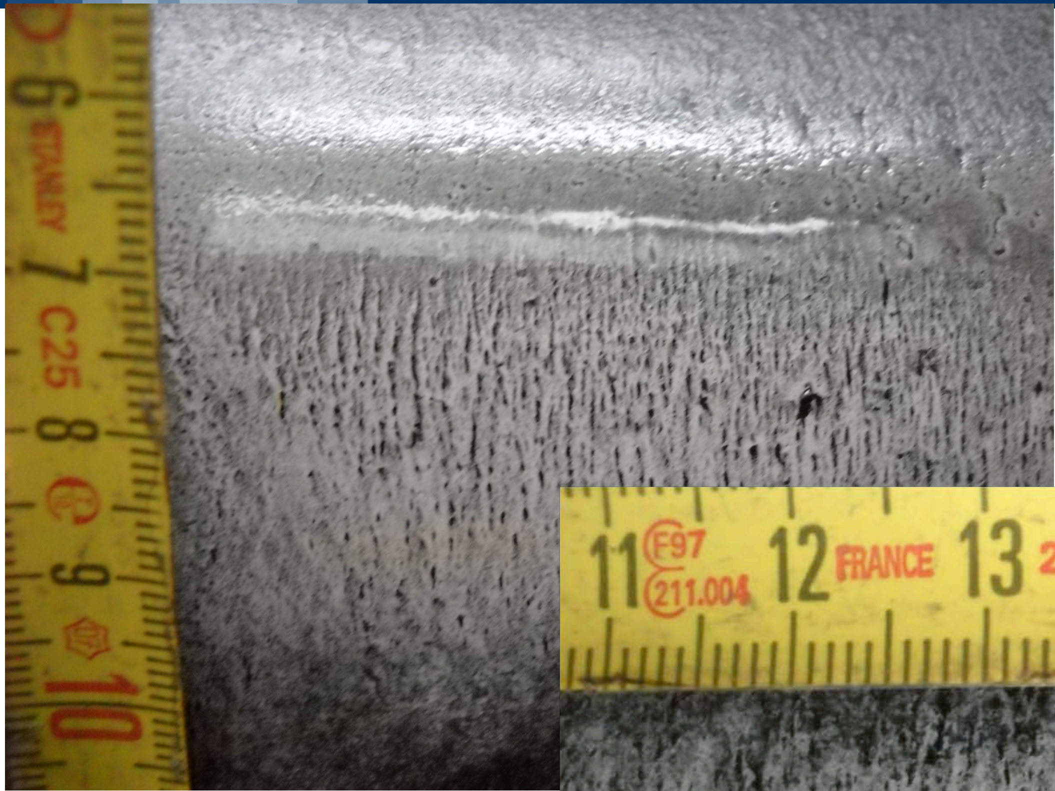


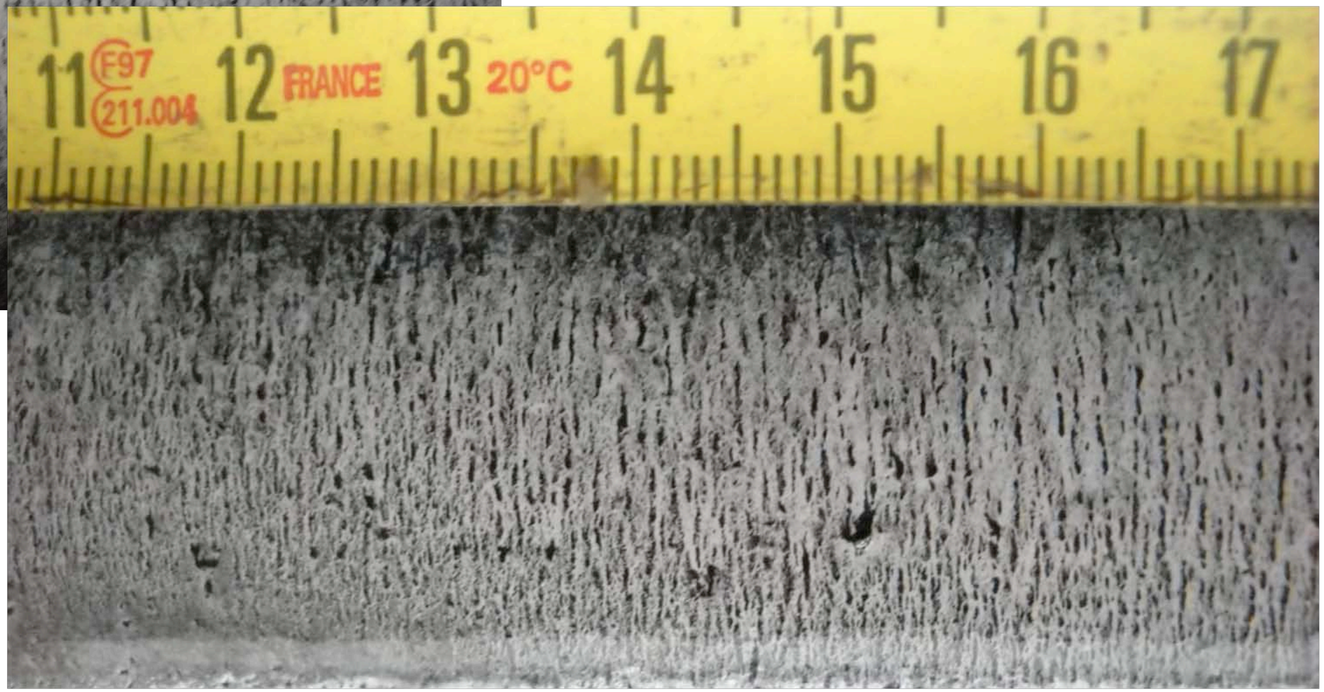
FULL SCALE TEST – 2^ AXLE (120 MPa) – INTERRUPTED (DATA at 30E6 cycles)



- The crack growth models predicts very well the length of maximum cracks;
- Newly formed cracks are observed → 'crack population' difficult

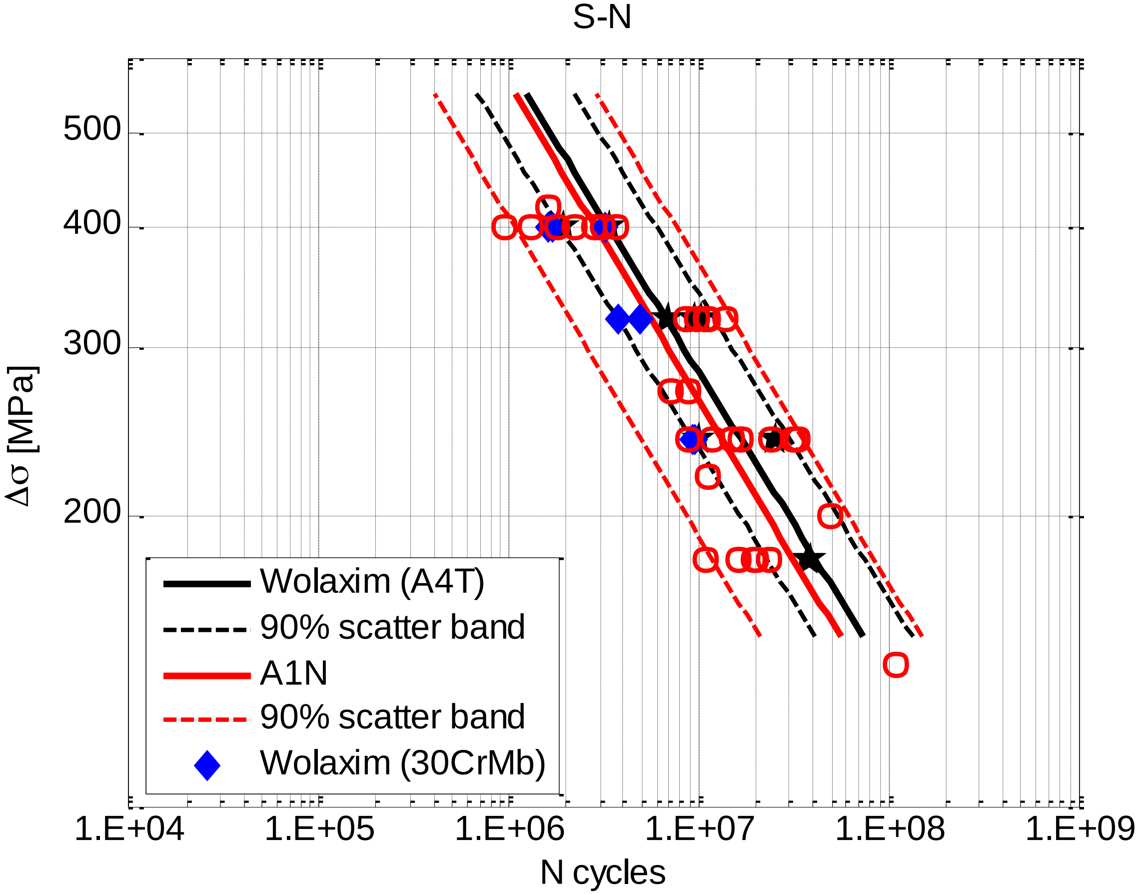
End of the test 30 10^6 cycles





Other data for 30NiCrMoV12

Comparison of the S-N diagram under corrosion fatigue



- Similar behaviour for A1N-A1T and A4T;
- 30 NiCrMoV12 data lie onto the lower band of the other data

Conclusion

In this presentation the results obtained at PoliMI on corrosion-fatigue of A1N steel have been shown. Main results can be summarized as:

•exposure of A1N to a mild corrosion (artificial rainwater) causes a dramatic reduction of fatigue life with the appearance of 'Hoddinott cracking';

•crack growth rate under corrosion-fatigue can be described with a simple model of the type:

$$\frac{dl}{dN} = B \cdot (\Delta S)^{\beta} \cdot l^{n}$$

- the mechanism of crack formation from the pits has been demonstrated for A1N-A1T and A4T;
- Fatigue damage occurs with an 'intense' cracking that could be taken as an indicator of damage;
- Tests for A4T and they confirm a similar S-N diagram, even if the complete mechanism is different from A1N

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