POLITECNICO DI MILANO





Wolaxim final meeting 24th-25th October 2012

Corrosion fatigue small-scale and full-scale tests

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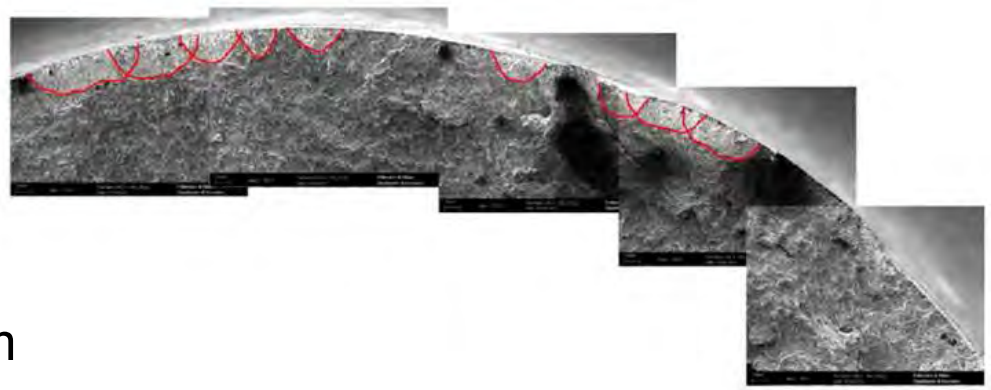
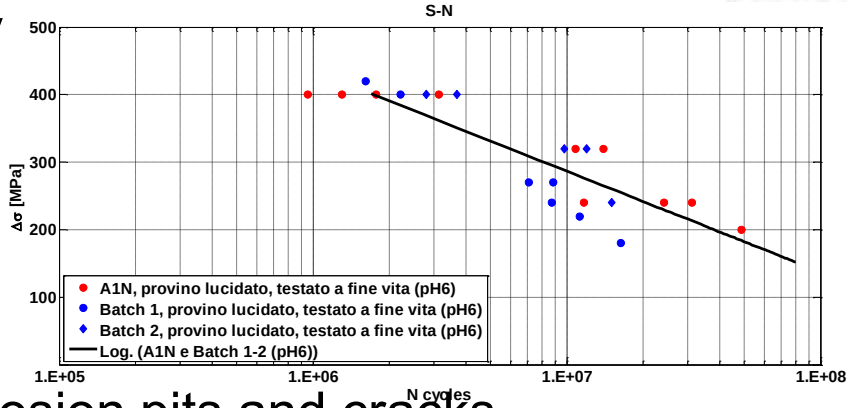
Open points at the begin of the project

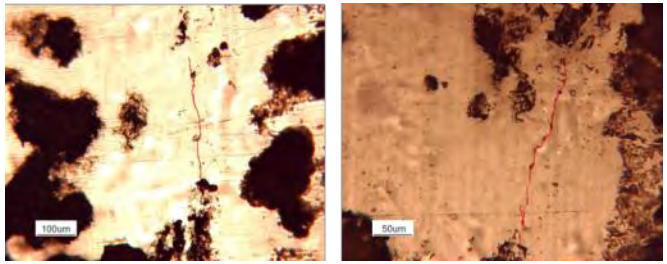
- Corrosion fatigue crack growth in A1N Material is affected by the coalescence phenomena;



- The corrosion fatigue SN diagram for A1N material seems continuously decreasing



- The damaged surface shows corrosion pits and cracks



Full scale tests RSSB project

Wolaxim experimental plan and aims

Small scale tests

- To consolidate the corrosion-fatigue SN diagram for the material A1N, but also to investigate the corrosion fatigue life of A4T and 30CrMb.
- To evaluate the effect of the corrosion on the crack propagation rate
- To study the coelescence phenomena and its interaction with the growth of the cracks
- To understand the mechanism of pit-to-crack transition

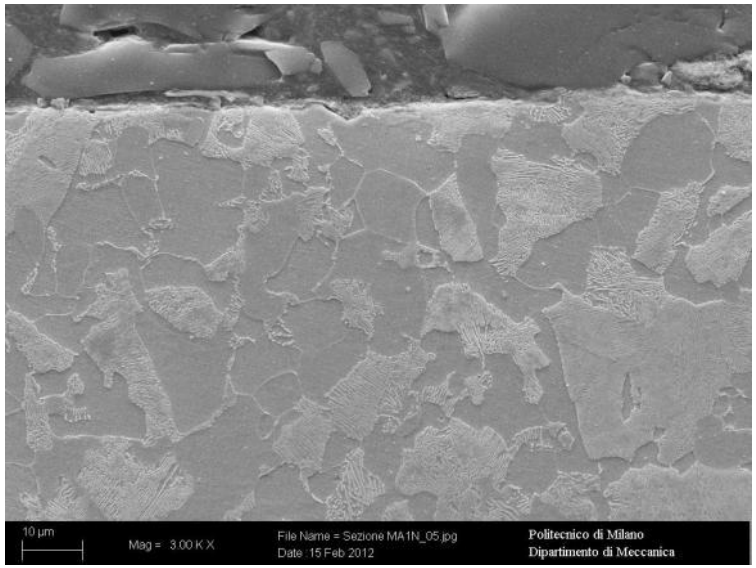
To set a corrosion fatigue model for the life prediction of railway axles

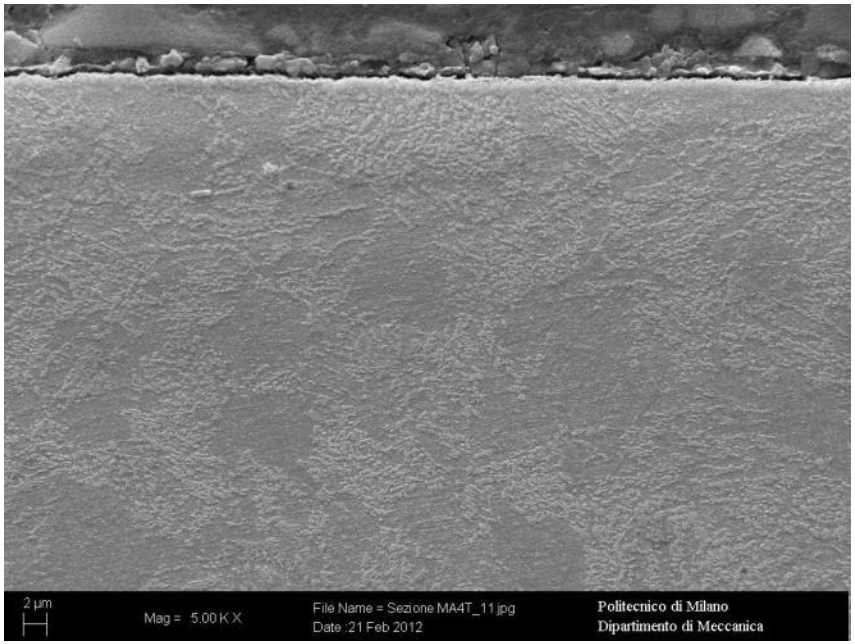
Full scale tests

- To investigate scale effect on the process of corrosion fatigue surface damage
- To validate the corrosion fatigue model

A1N Ferritic-perlitic microstructure

Rp0.2= 395 MPa
Rm=597 MPa



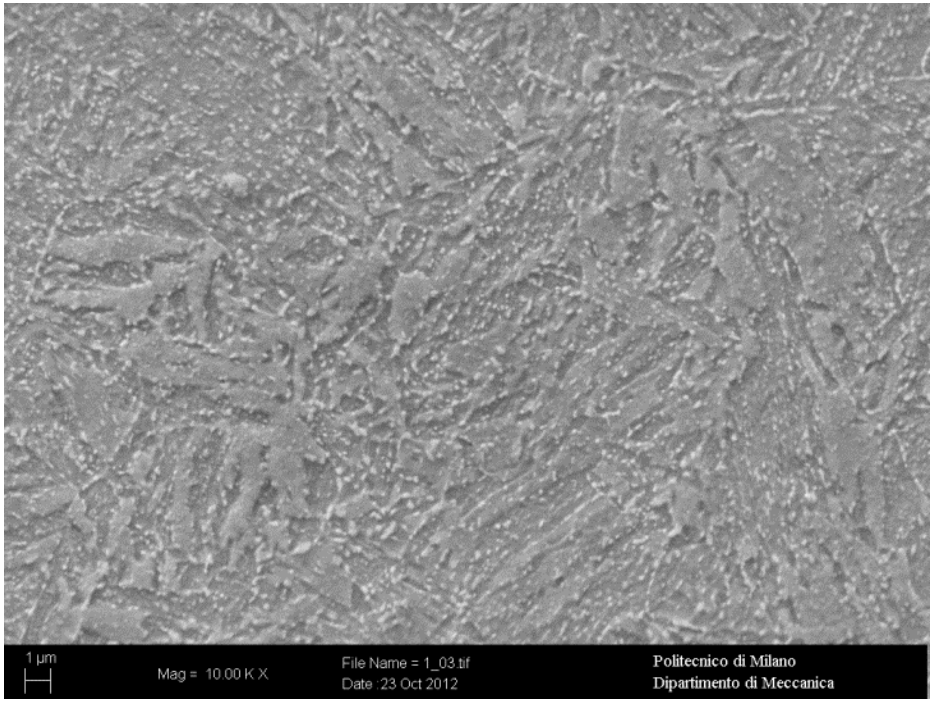


A4T globular perlite microstructure

Rp0.2= 531 MPa
Rm=705 MPa

30CrMb Bainitic microstructure

Rp0.2= 878 MPa
Rm=1045 MPa



Programme of corrosion fatigue small scale tests

Load level (σ) [MPa]	Number of failure tests	Number of the interrupted tests	Estimated number of cycles	Frequency [Hz]	Total time [days]
160	2	--	14 10^6	10	20
120	2	2	55 10^6	10	67
90	2	2	138 10^6	10	164
				Total time A1N	251

Table 1 Rotating bending tests on A1N smooth small scale specimens.

Load level (σ) [MPa]	Number of failure tests	Number of the interrupted tests	Estimated number of cycles	Frequency [Hz]	Total time [days]
200	2	2	5,5 10^6	10	10
160	2	2	19,5 10^6	10	26
120	2	2	55 10^6	10	67
90	2	2	138 10^6	10	164
				Total time A4T	267

Table 2 Rotating bending tests on A4T smooth small scale specimens.

Load level (σ) [MPa]	Number of failure tests	Number of the interrupted tests	Estimated number of cycles	Frequency [Hz]	Total time [days]
160	2	0	14 10^6	10	18
120	2	0	40 10^6	10	48
90	2	0	100 10^6	10	118
				Total time 30CrMb	184

Table 3 Rotating bending tests on 30CrMb smooth small scale specimens.

Summary of A1N tests

- End life tests in order to consolidate the SN diagram of this material

  (**8 tests**)

- Tests interrupted at a fixed percentage of the fatigue life (and not restarted), to study the evolution of corrosion pits, the pit-to-crack transition and the coalescence of cracks at different stages and for different stress levels

  (**16 tests**)

- Tests at low stress level, interrupted and restarted each $4 \div 6\ 10^5$ cycles for the measurements of crack growth rate

  (**2 tests**)

Tests and related analysis on A1N material have been completed

Summary of A1N tests

Material	Sample	ΔS [MPa]	Cycles	Notes
A1N	ML2	400	$1\ 10^6$	Interrupted 11% Life
A1N	ML3	400	$2\ 10^6$	Interrupted 22% Life
A1N	ML4	400	$3\ 10^6$	Interrupted 33% Life
A1N	ML5	400	$4\ 10^6$	Interrupted 44% Life
A1N	ML6	400	$5\ 10^6$	Interrupted 55% Life
A1N	ML7	400	$6\ 10^6$	Interrupted 66% Life
A1N	ML8	400	$7\ 10^6$	Interrupted 77% Life
A1N	ML9	400	$8\ 10^6$	Interrupted 88% Life
A1N	ML10	400	$9\ 10^6$	End life
A1N	ML11	400	$9\ 10^6$	End life
A1N	W2	320	$8.4\ 10^6$	End life
A1N	W3	240	$16.4\ 10^6$	End life
A1N	W4	180	$10\ 10^6$	Interrupted 50% Life
A1N	W7	180	$23.6\ 10^6$	End life
A1N	W9	240	$2\ 10^6$	Interrupted 20% Life
A1N	W10	240	$33\ 10^6$	End life
A1N	W11	180	$19.4\ 10^6$	End life
A1N	W12	180	$11\ 10^6$	End life
A1N	W13	180	$5.1\ 10^6$	Interrupted 10% Life
A1N	W14	240	$0.8\ 10^6$	Interrupted <5% Life
A1N	W16	180	$20.2\ 10^6$	End life
A1N	W17	140	$110.3\ 10^6$	End life
A1N	W18	140	$8.5\ 10^6$	Interrupted 10% Life
A1N	W19	180	$7.4\ 10^6$	Interrupted 30% Life
A1N	W20	180	$6.5\ 10^6$	Interrupted each $6\ 10^5$ cycles
A1N	W26	240	$2.1\ 10^6$	Interrupted each $4\ 10^5$ cycles

Summary of A4T tests

- End life tests obtain the SN diagram of this material and to compare it with the SN diagram of the A1N steel. (**11 tests**)

- Tests interrupted at a fixed percentage of the fatigue life (and not restarted), to study, as for A1N, the evolution of corrosion pits, the pit-to-crack transition and the coalescence of cracks at different stages and for different stress levels (**15 tests**)

- Tests at low and high stress level, interrupted and restarted each $2 \div 6\ 10^5$ cycles for the measurements of crack growth rate (**7 tests**)

For *A4T material the scheduled tests and additional have been completed.*

Summary of A4T tests

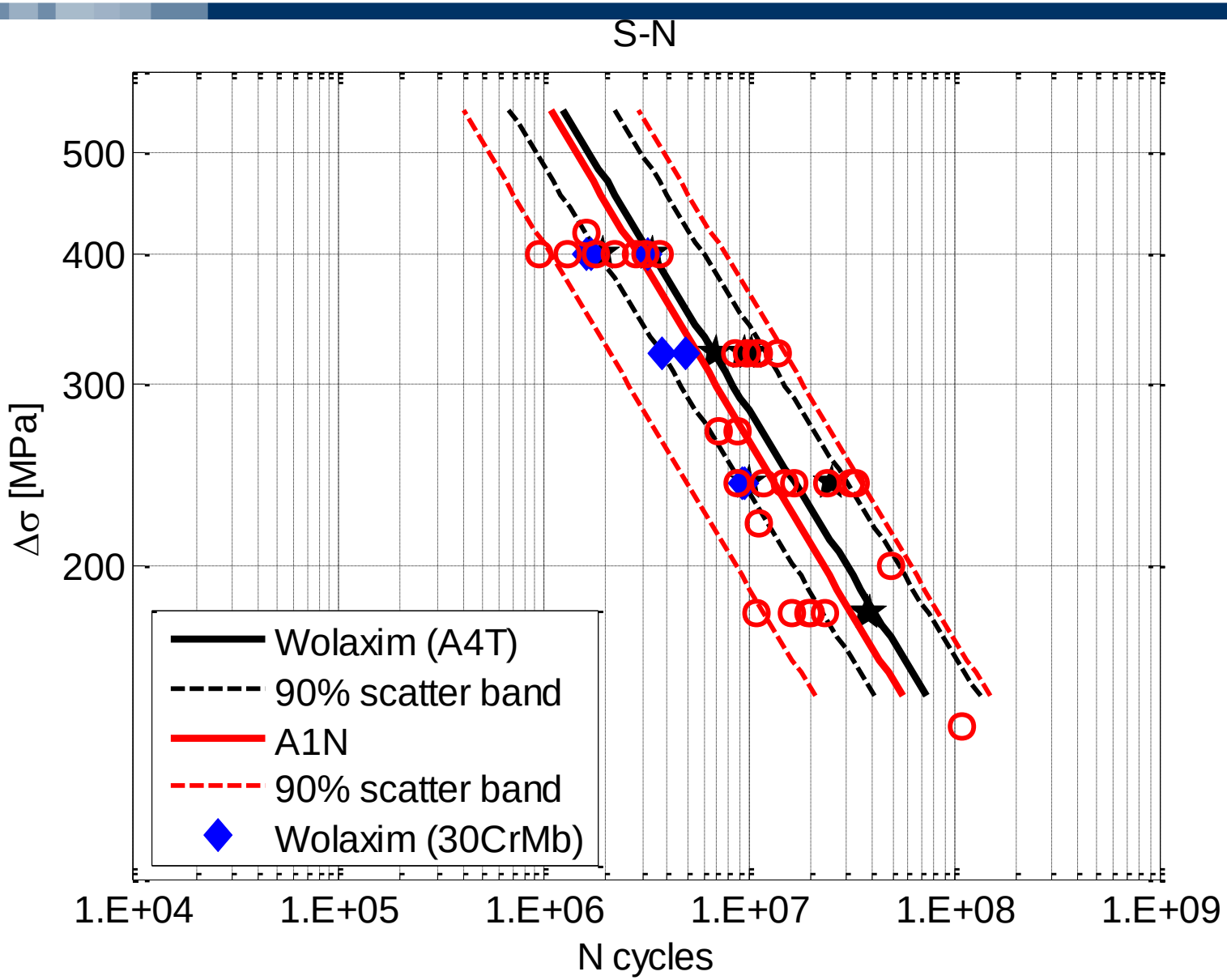
Material	Sample	ΔS [MPa]	Cycles	Notes
A4T	W21	400	$1.9\ 10^6$	End Life
A4T	W22	320	$10.2\ 10^6$	End Life
A4T	W23	240	$10.1\ 10^6$	End Life
A4T	W24	240	$25.0\ 10^6$	End Life
A4T	W27	180	$6.5\ 10^6$	Interrupted each $6\ 10^5$ cycles
A4T	W28	400	$5\ 10^6$	Interrupted 25% Life
A4T	W29	400	$2\ 10^5$	Interrupted 10% Life
A4T	W30	320	$5\ 10^5$	Interrupted 10% Life
A4T	W31	400	$1\ 10^5$	Interrupted 5% Life
A4T	W32	240	$2\ 10^5$	Interrrupted early stage of Life
A4T	W33	180	$2\ 10^5$	Interrrupted early stage of Life
A4T	W34	180	$38.2\ 10^5$	End life
A4T	W35	320	$9.5\ 10^6$	End Life
A4T	W36	240	$2.8\ 10^6$	Interrupted each $4\ 10^5$ cycles
A4T	W38	400	$1\ 10^6$	Interrupted each $2\ 10^5$ cycles
A4T	W39	180	$39.1\ 10^6$	End life
A4T	W41	320	$1.3\ 10^6$	Interrupted each $2.5\ 10^5$ cycles
A4T	W48	180	$6.0\ 10^6$	Interrupted 10% Life
A4T	W49	180	$0.8\ 10^6$	End Life
A4T	W50	240	$0.8\ 10^6$	Interrupted 5%Life
A4T	W51	240	$6.0\ 10^6$	Interrupted 25% Life
A4T	W52	240	$2.0\ 10^6$	Interrupted 10% Life
A4T	W54	240	$2.9\ 10^6$	Interrupted each $4\ 10^5$ cycles
A4T	W55	320	$1.8\ 10^6$	Interrupted each $4\ 10^5$ cycles
A4T	W57	400	$1.5\ 10^6$	Interrupted each $2.5\ 10^5$ cycles
A4T	W58	320	$1.5\ 10^6$	Interrrupted 15% Life
A4T	W61	320	$1.0\ 10^6$	Interrupted 10% Life
A4T	W62	320	$6.9\ 10^6$	End Life
A4T	W63	180	$2.0\ 10^6$	Interrupted 5% Life
A4T	W64	180	$10\ 10^6$	Interrupted 25% Life
A4T	W65	400	$3.38\ 10^5$	End life
A4T	W67	400	$3.39\ 10^6$	End life
A4T	W70	320	$0.2\ 10^6$	Interrupted early stage of life

Tests on 30CrMb material

Material	Sample	ΔS [MPa]	Cycles	Notes
30CrMb	W44	320	$3.72\ 10^6$	End Life
30CrMb	W45	400	$1.69\ 10^6$	End Life
30CrMb	W47	400	$1.62\ 10^6$	End Life
30CrMb	W71	320	$4.9\ 10^6$	End Life
30CrMb	W72	240	$9.47\ 10^6$	End Life
30CrMb	W73	320	$9.15\ 10^6$	End Life

For *30CrMb material the scheduled have been completed.*

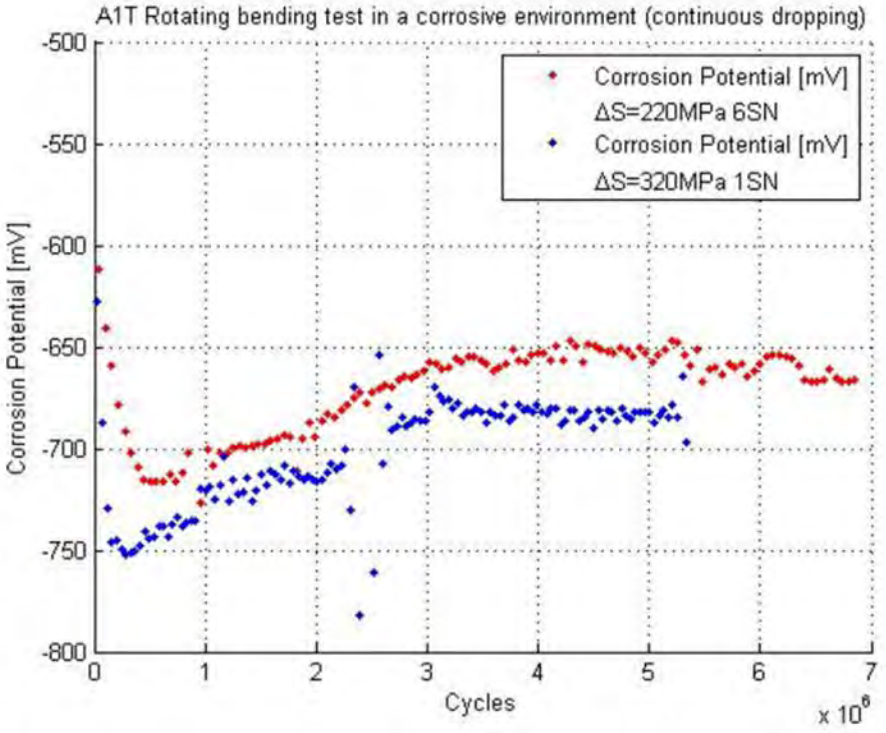
SN diagram

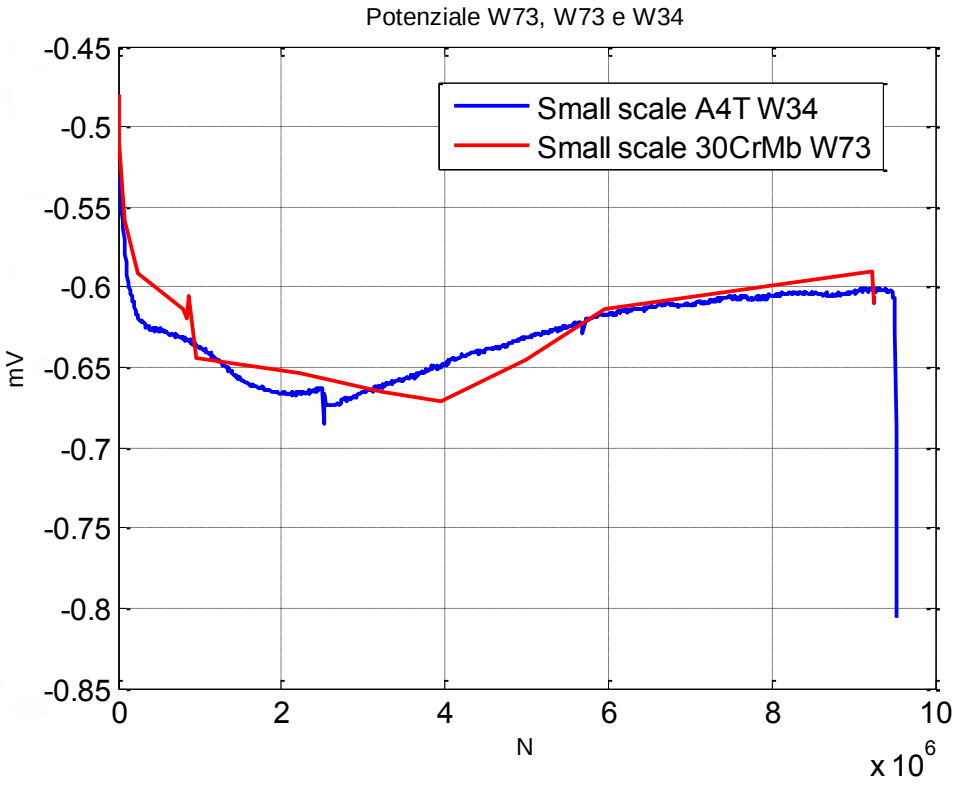

S-N
500
400
300
200
Δσ [MPa]
1.E+04
1.E+05
1.E+06
1.E+07
1.E+08
1.E+09
N cycles
Wolaxim (A4T)
90% scatter band
A1N
90% scatter band
Wolaxim (30CrMb)

Observations

- Atmospheric corrosion has a significant influence on the fatigue life of the investigated materials
- The trend continuously decreasing of the diagram is confirmed for A1N, A4T and 30CrMb steels.
- The presence of rainwater can cause failures at stress levels well below the EN13103/4 design limit ($\Delta\sigma$ = 362 MPa),
- the BASS design limit ($\Delta\sigma_{design}$=220 MPa), which is valid for steels with UTS of 550-650 MPa, is comparable to present experimental results.

Electrical potential, small scale tests





Corrosion fatigue process

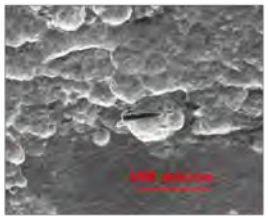
Stage	Appearence	Notes	Image
Pits	Formation at the bottom of the primary corrosion pits of a secondary pit	Electrochemical cell at the bottom of the primary pits	
	Nucleation of a small crack at the bottom of the primary pit	The presence of the secondary pit has enhanced the stress concentration at the bottom of the primary pit	
	The small crack go out of the pit	The small crack propagates	
Pit-to-crack transition			
Small cracks	Propagation of small cracks	The coalescence occurs when the cracks length is at least 300 micron. The rate of propagation of the small cracks depends on the stress level	
	and/without		
	coalescence		
Small to long cracks transition			
Long cracks	Propagation of macro cracks	When the crack length is greater then 1 mm, than the crack growth rate tends to the crack growth rate in air.	

History of the damage

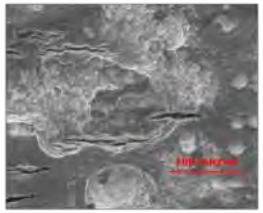
ΔS=180MPa

2 10^5 cycles

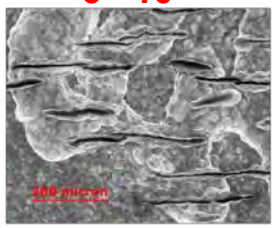
8 10^5



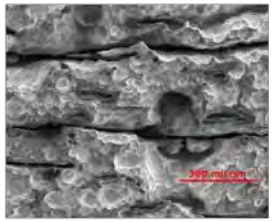
2 10^6



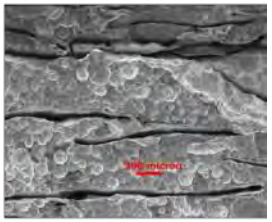
6 10^6



10 10^6

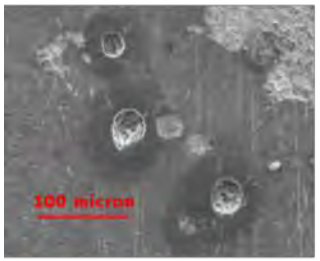


39 10^6

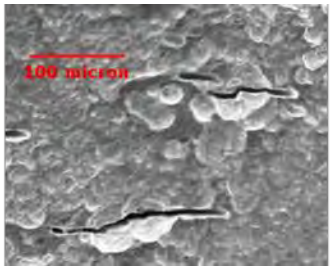


ΔS=240MPa

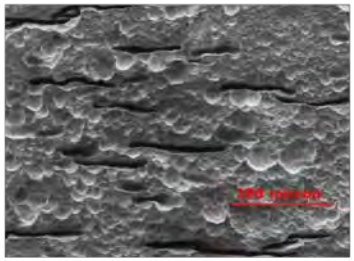
2 10^5 cycles



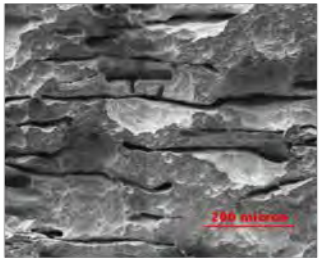
8 10^5



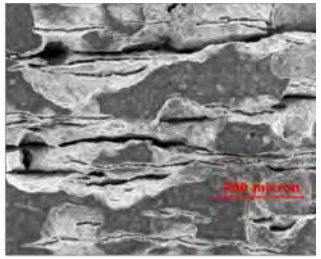
2 10^6



6 10^6

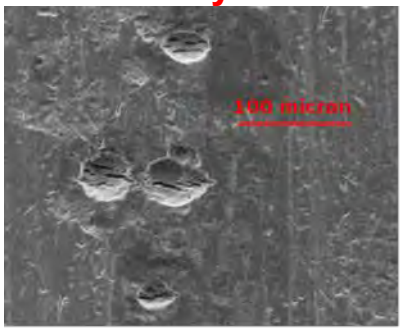


25 10^6

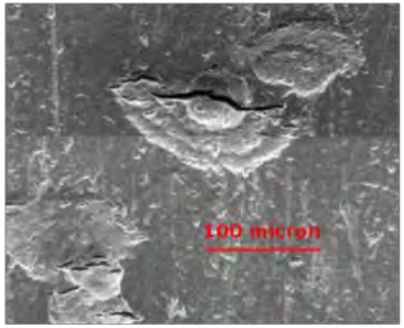


ΔS=400MPa

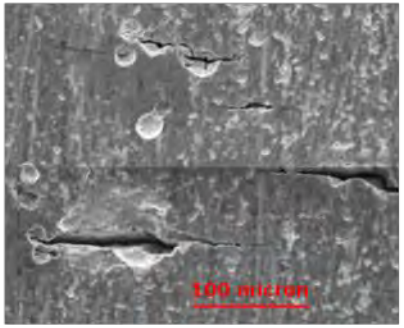
1 10^5 cycles



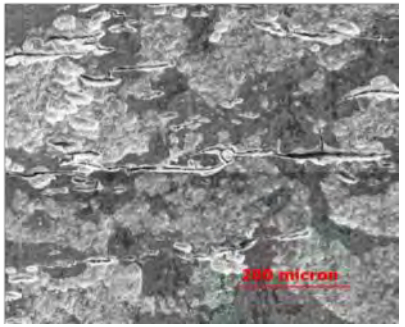
2 10^5



5 10^5

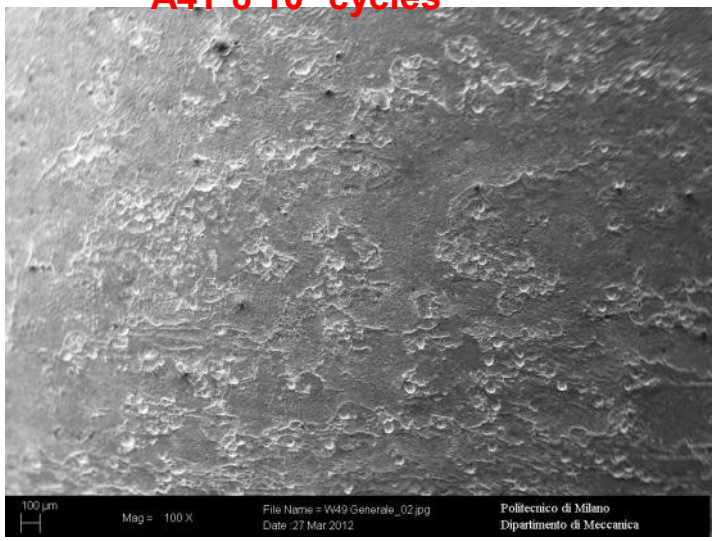


1.9 10^6

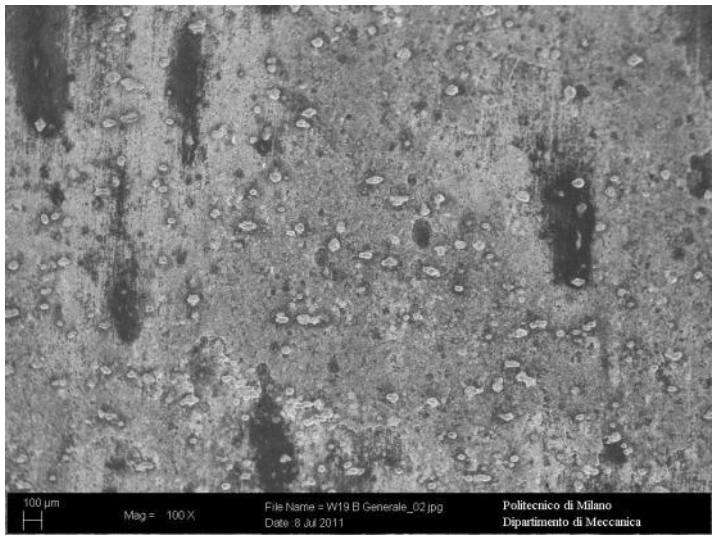


First stage of the Fatigue Life 180 MPa

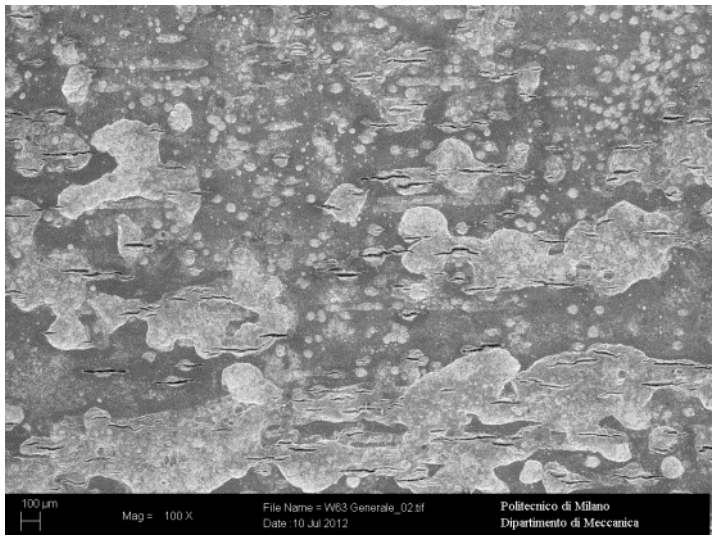
A4T 8 10^6 cycles



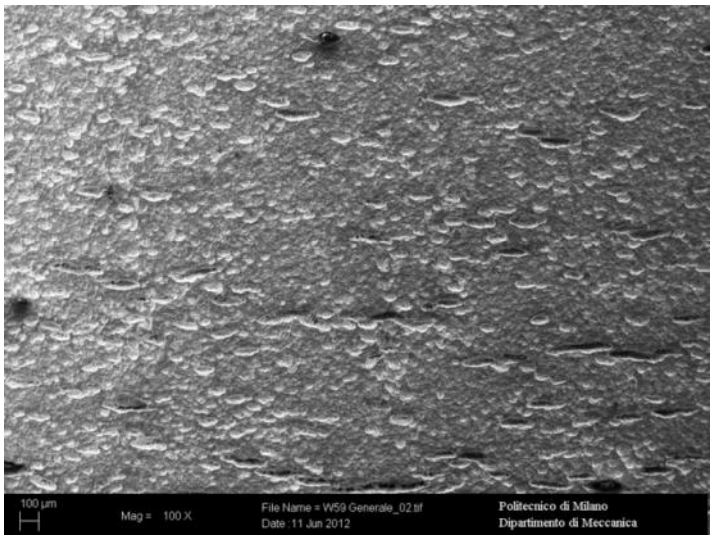
A1N 8 10^6 cycles



A4T 2 10^6 cycles

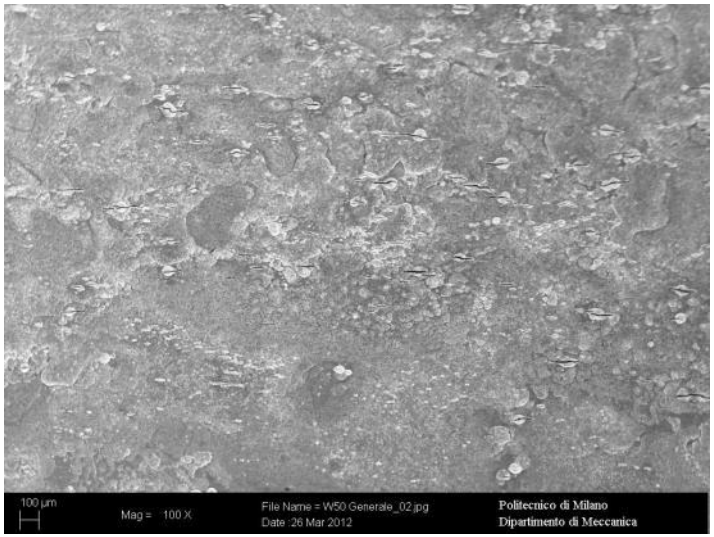


A1N 2 10^6 cycles

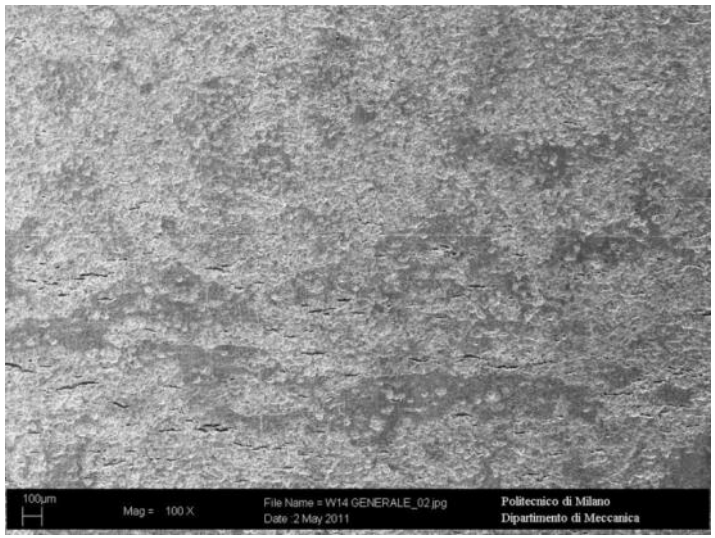


First stage of the Fatigue Life 240 MPa

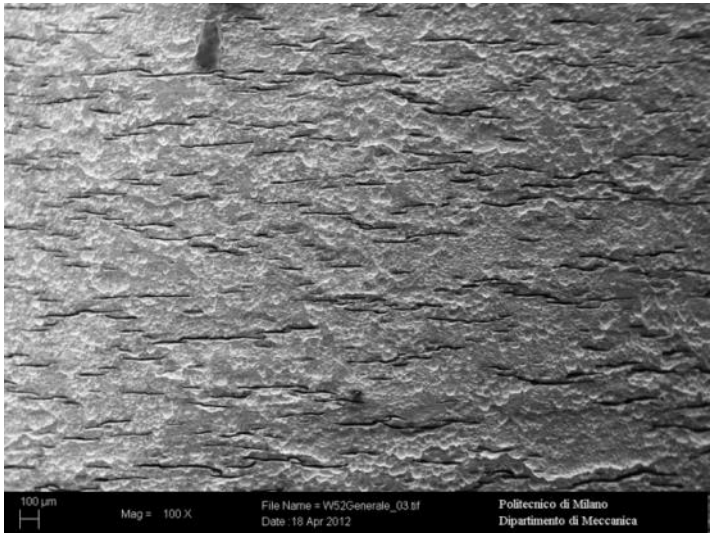
A4T 8 10^5 cycles



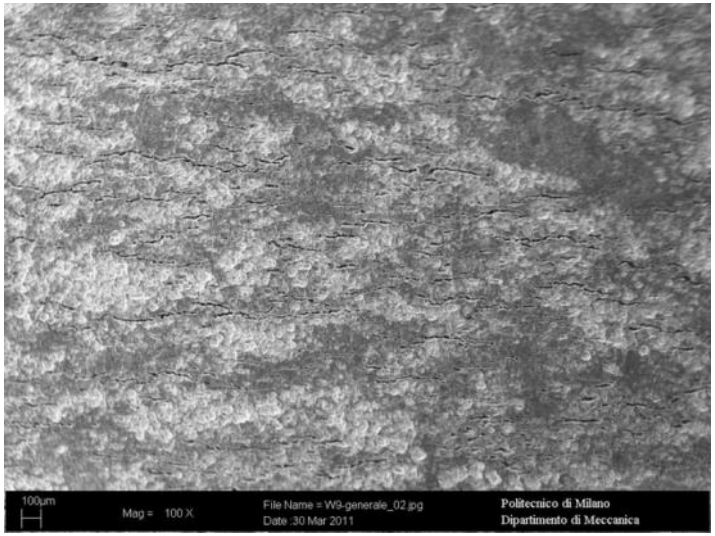
A1N 8 10^5 cycles



A4T 2 10^6 cycles



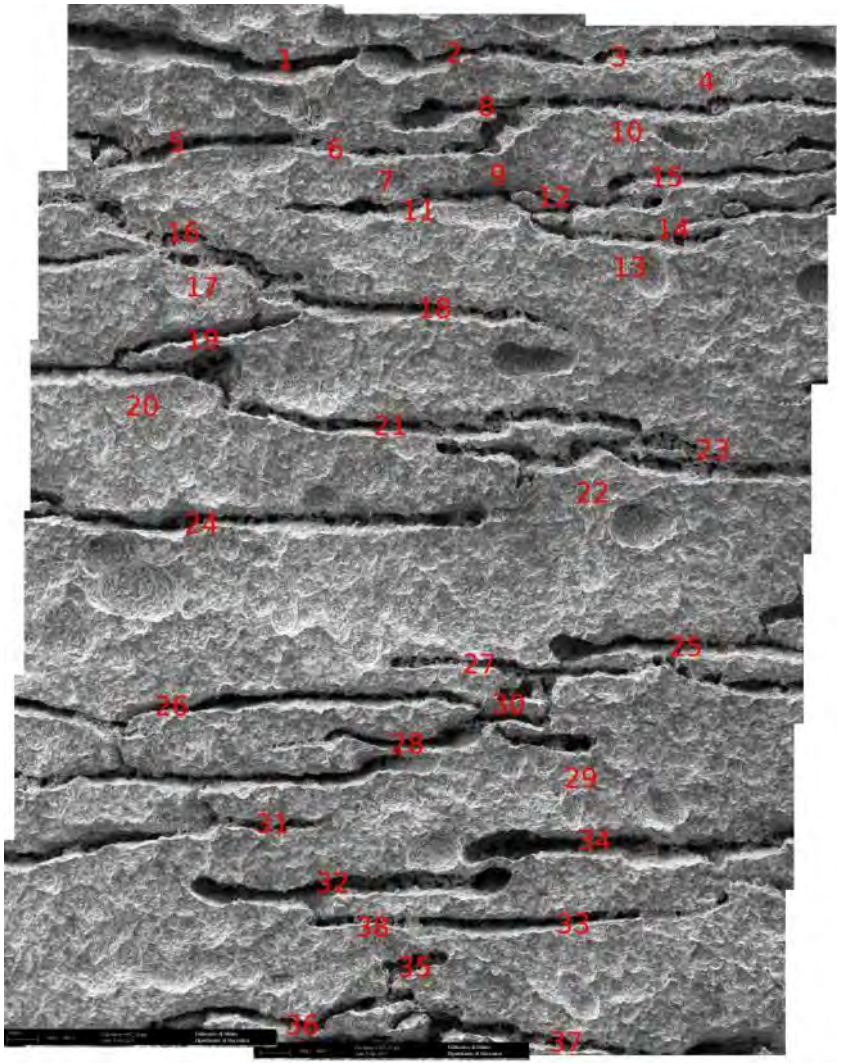
A1N 2 10^6 cycles



Damage of the surface

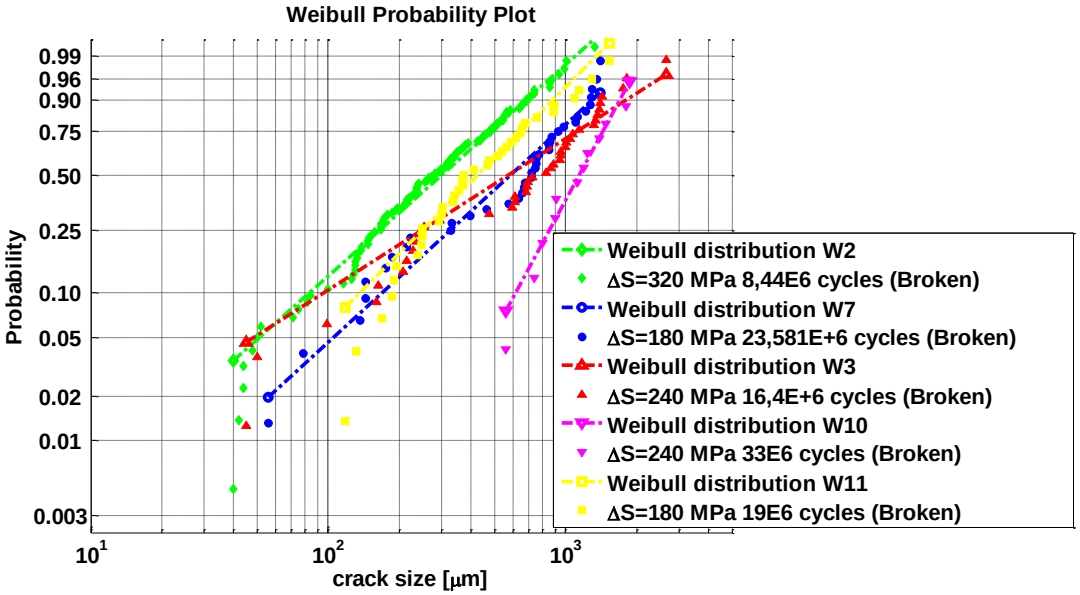
- Chemical cleaning of the surface
- Representative area equal to 9 mm^2
- The length of the surface cracks in a representative area is described by a Weibull distribution with α the location and β the shape parameter

$$F(l) = 1 - \exp\left[-\frac{l}{\alpha}\right]^{\beta}$$

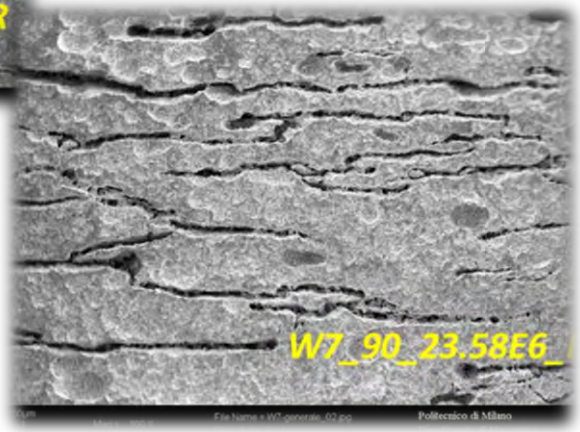


A1N Specimen W7, ΔS = 180 MPa. Broken at 23.6 10^6 cycles

Broken specimens (A1N)



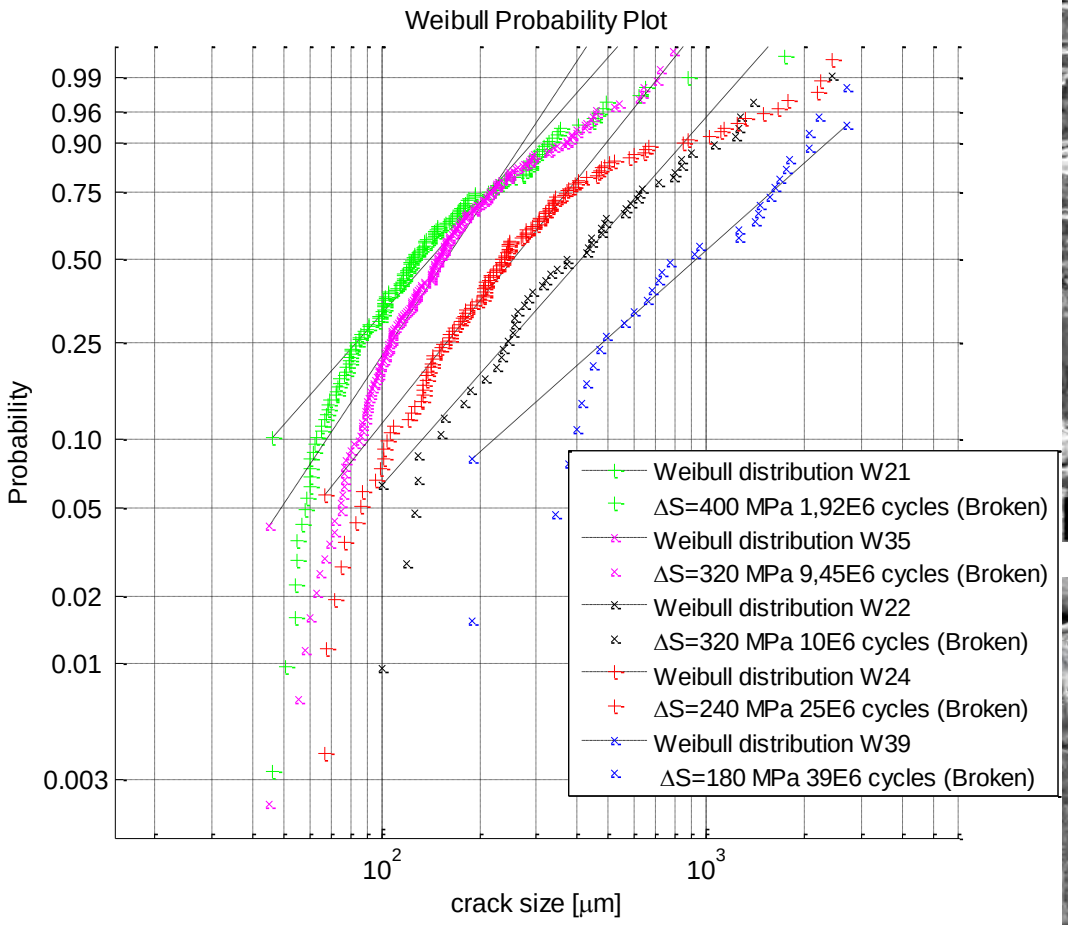
Specimen W2, ΔS=320 MPa.
Broken at 8.44 10^6

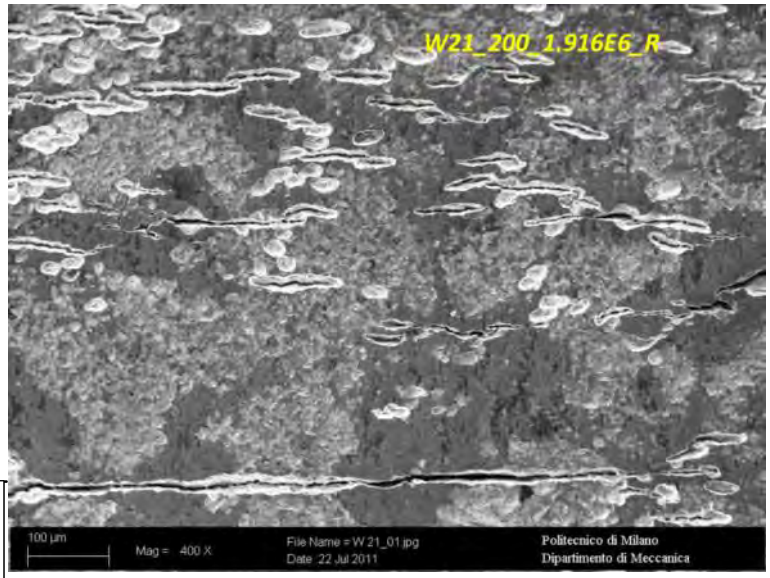


Specimen W7, ΔS=180 MPa.
Broken at 8.44 10^6

- The average length of the crack increases
- The number of cracks decrease due to the coalescence phenomena

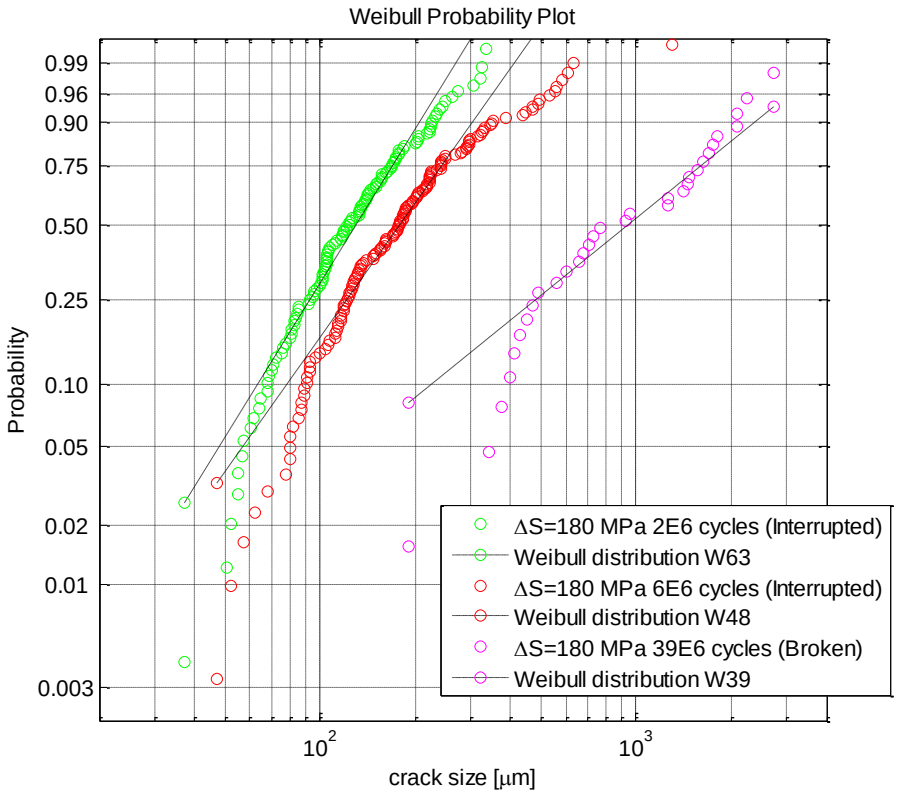
Broken specimen (A4T)

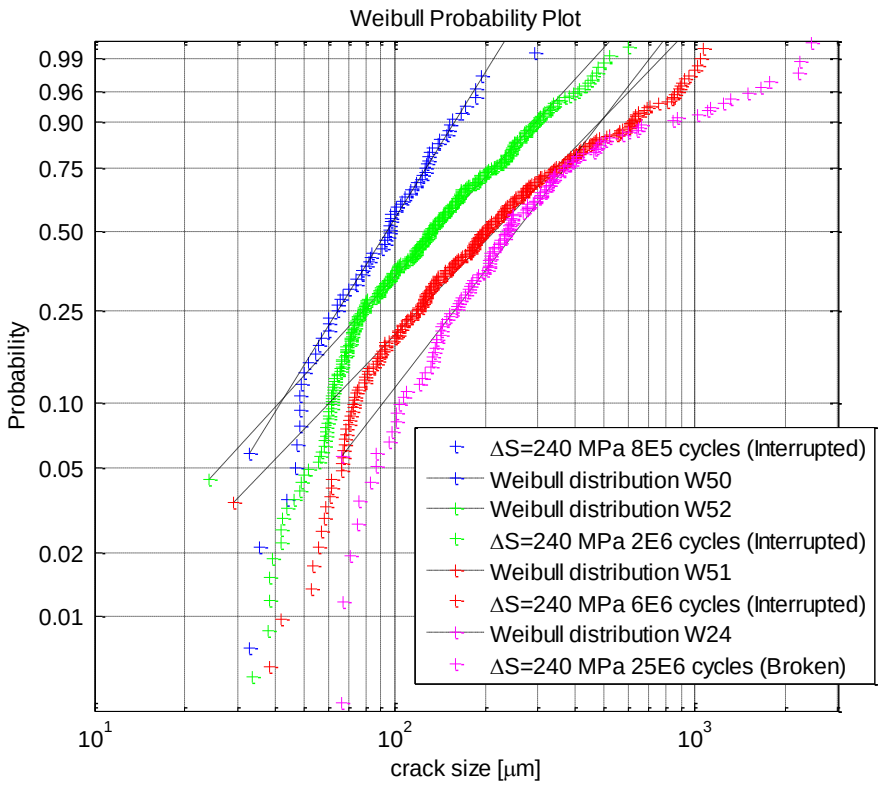




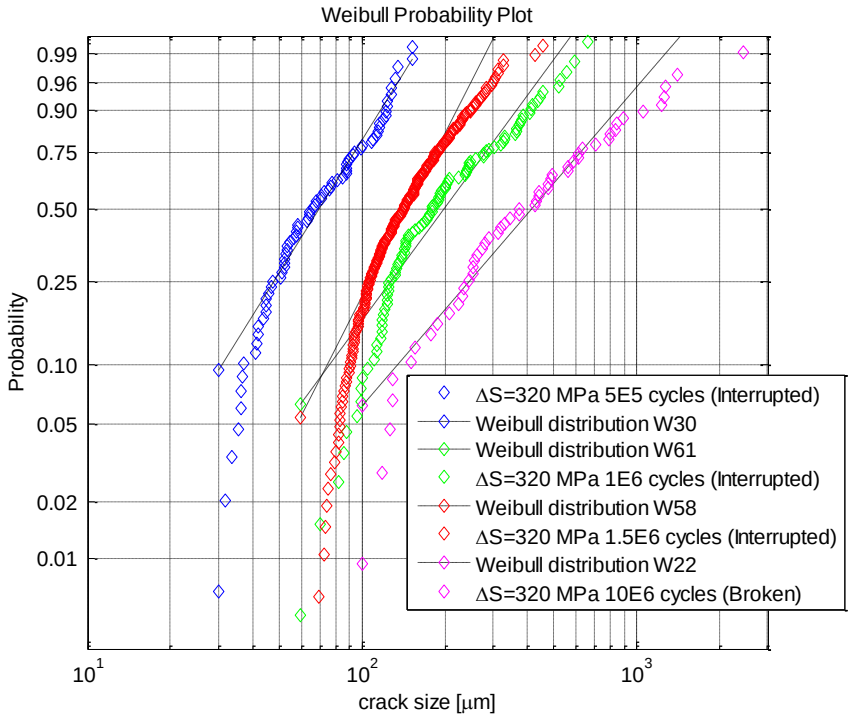
Can be observed a large number of cracks and pits with respect to the A1N steel.

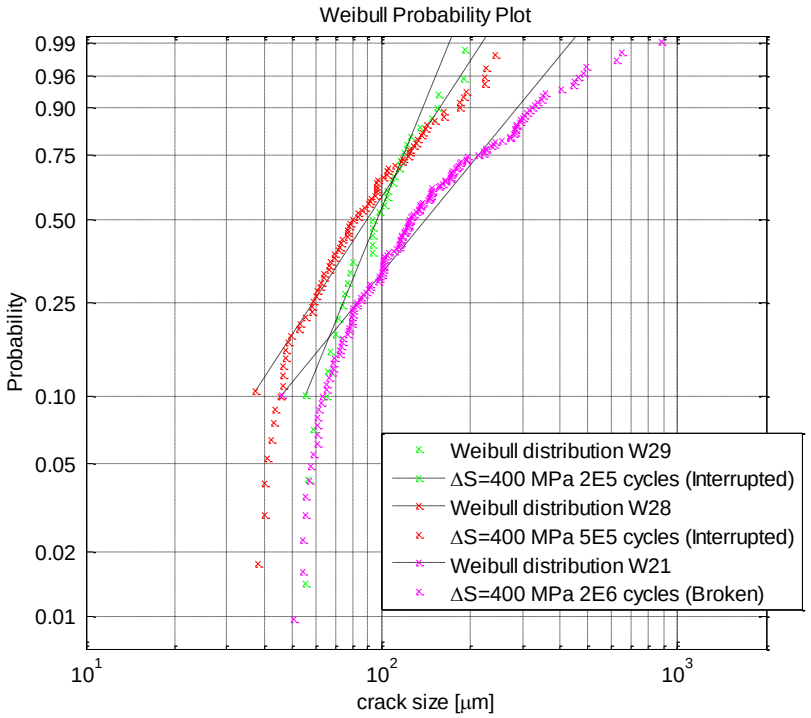
A4T interrupted tests

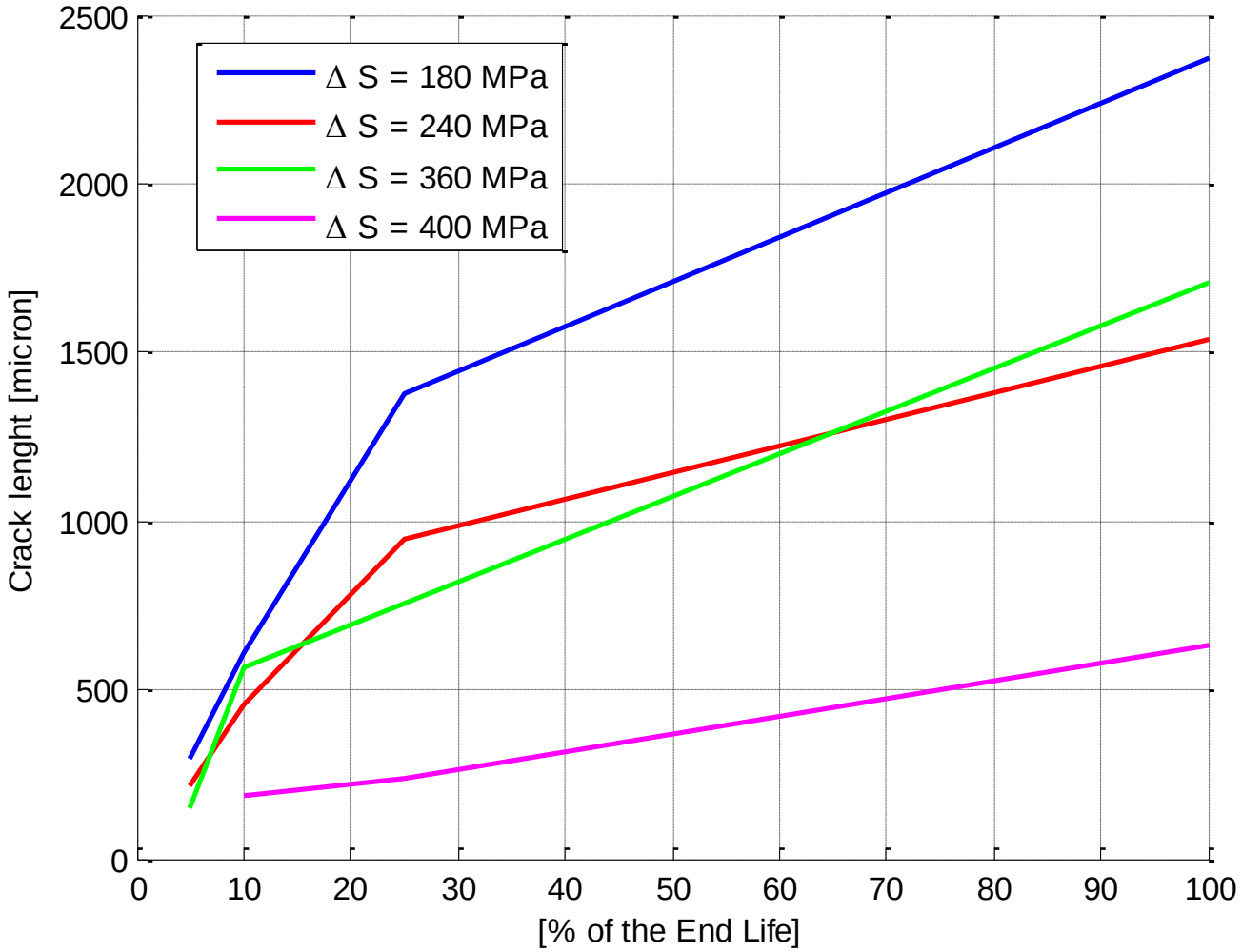




A4T Interrupted tests






Δ S = 180 MPa
Δ S = 240 MPa
Δ S = 360 MPa
Δ S = 400 MPa
Crack lenght [micron]
[% of the End Life]
0
500
1000
1500
2000
2500
0
10
20
30
40
50
60
70
80
90
100

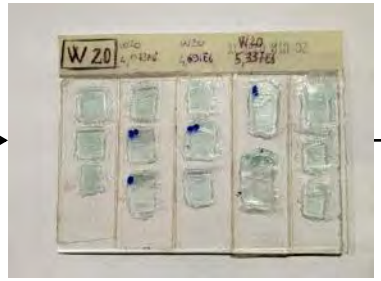
Crack propagation tests

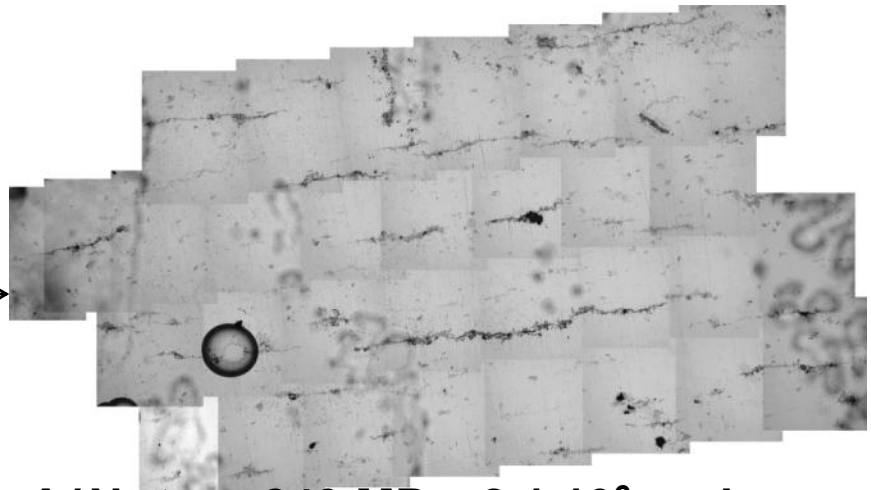
Microdrilled specimen has been tested at:

$\Delta\sigma$ = 180 MPa and 240 MPa for A1N material
$\Delta\sigma$ = 180, 240, 360, and 400 MPa for A4T material

The nucleation and the propagation of micro-cracks from the micro-holes and/or corrosion pits in proximity to the micro-holes, were monitored during the tests.

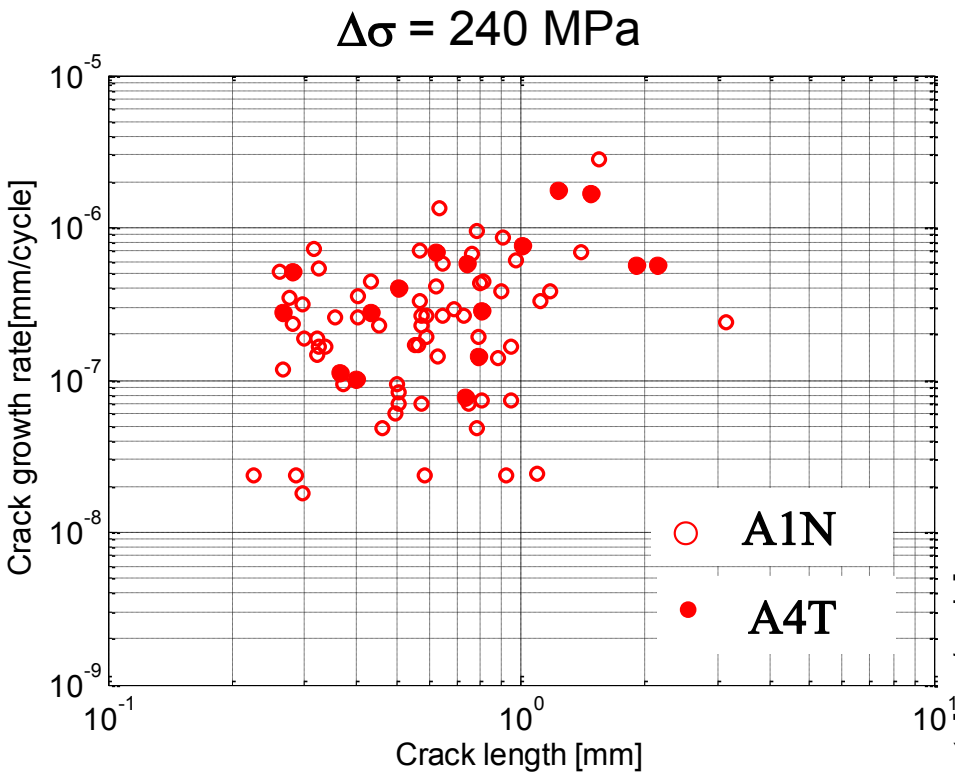
Every 2-6 10^5 cycles the test was interrupted to remove rust, to clean the specimen and to take plastic replicas of the propagating cracks

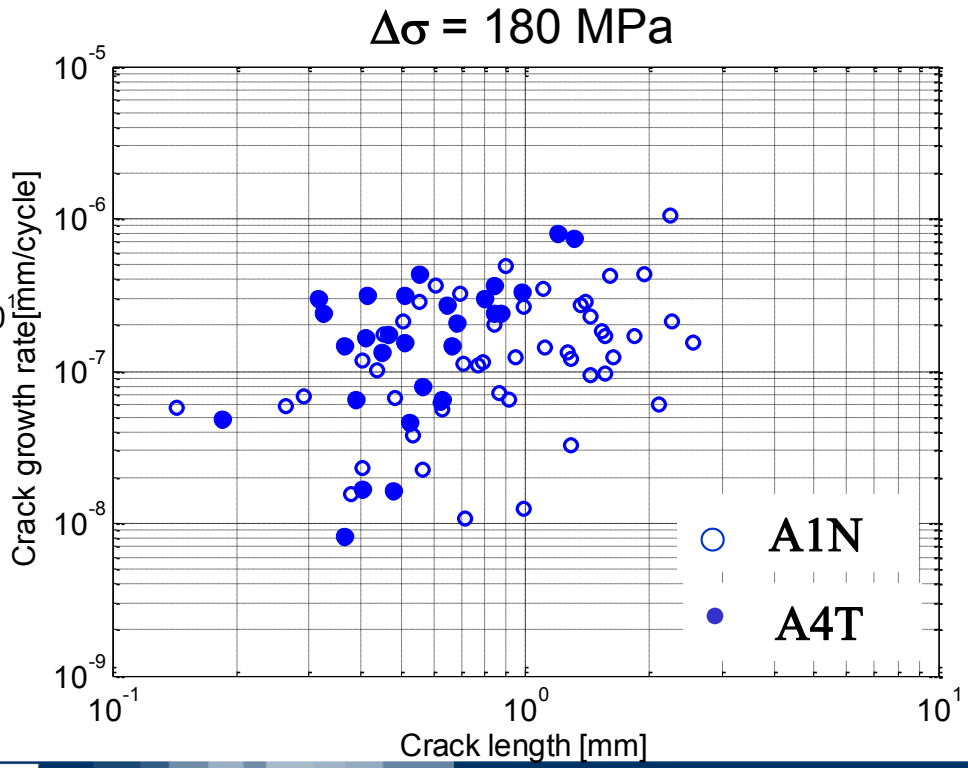




A1N $\Delta\sigma$ = 240 MPa 2.1 10^6 cycles

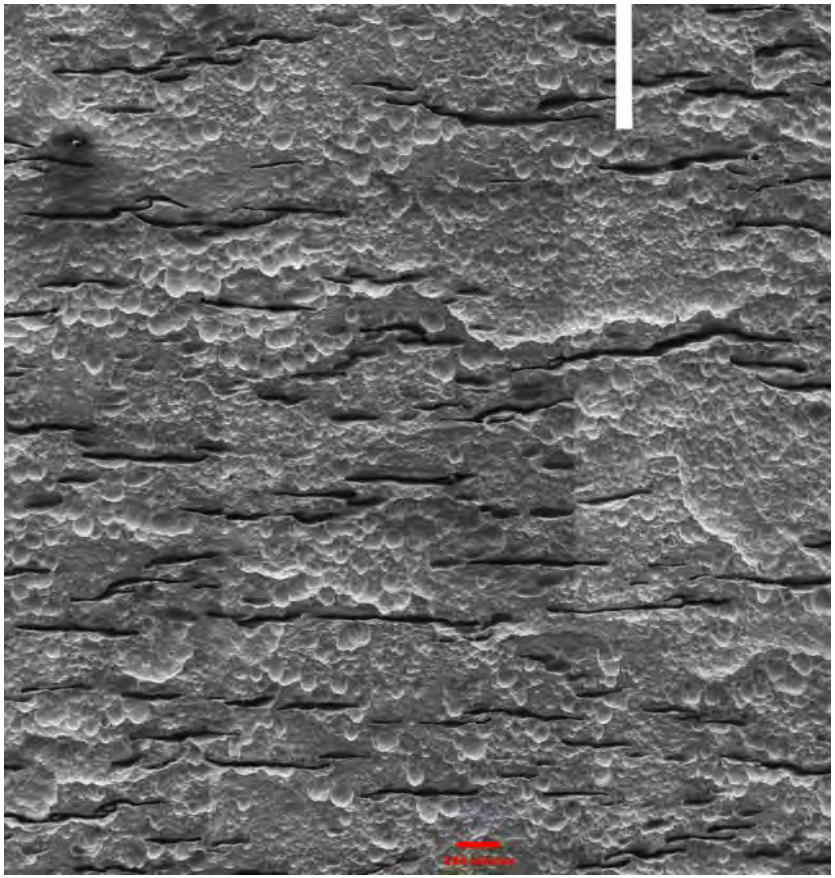
Comparison A1N-A4T

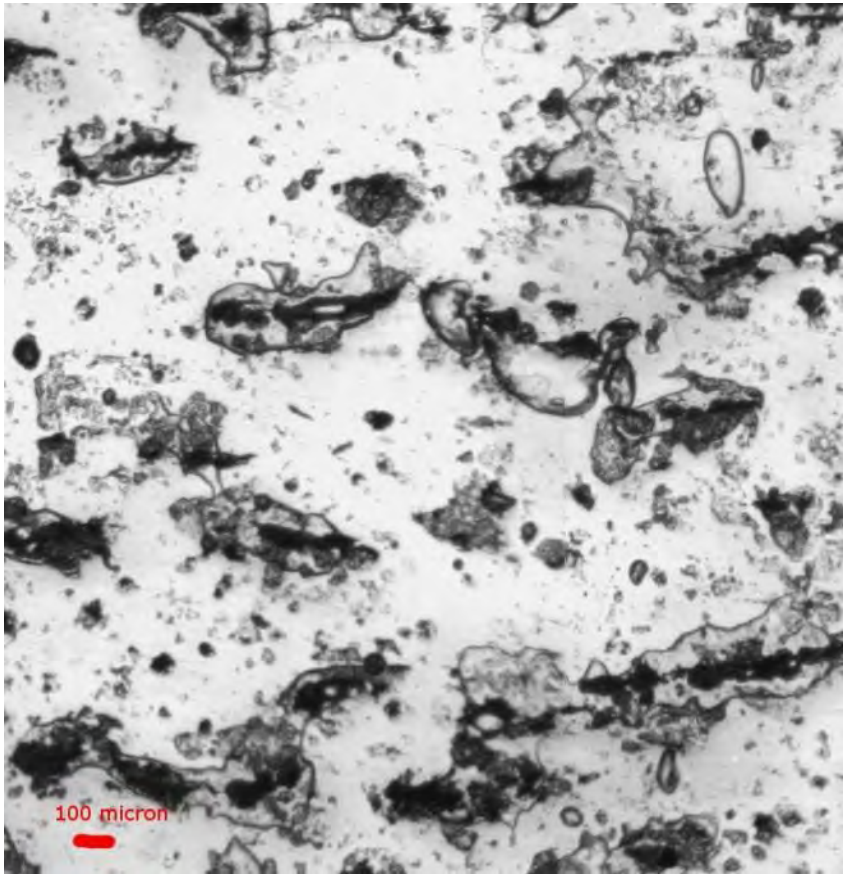




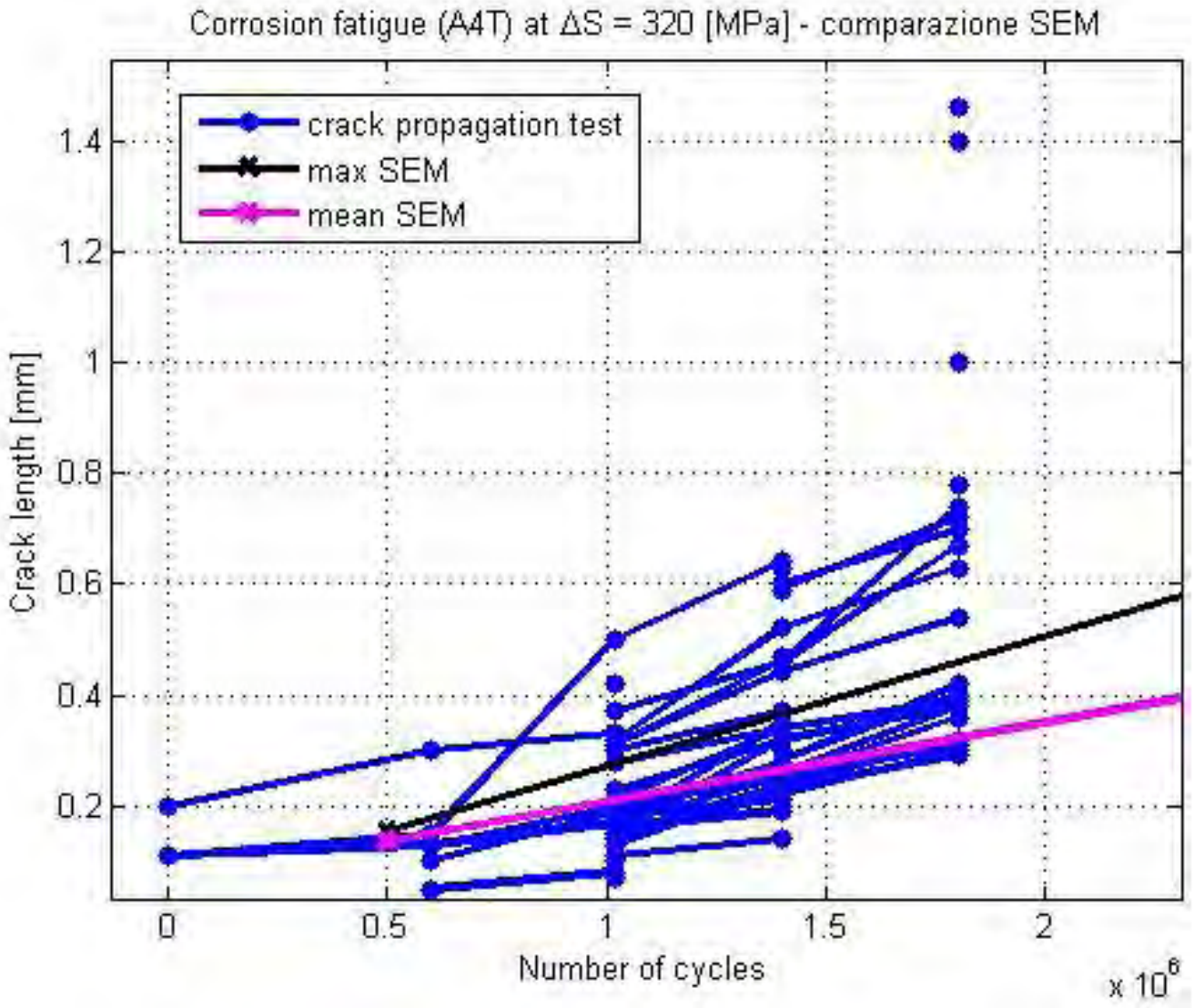
Interrupted test and crack propagation test 240 MPa

W54(2.5E6) – W52_interrupted(2E6) (240 MPa)

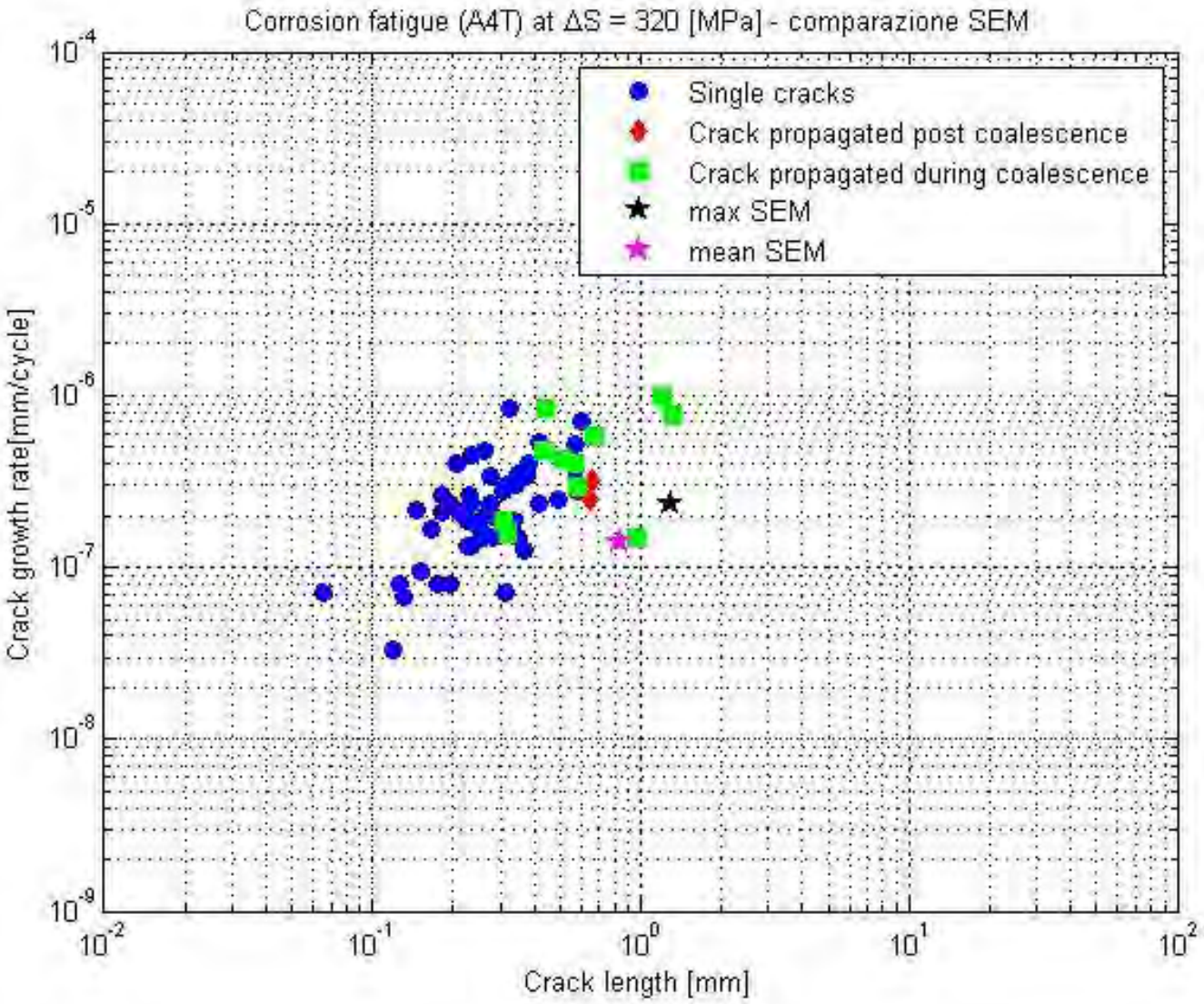




Propagation of single cracks A4T 320 MPa

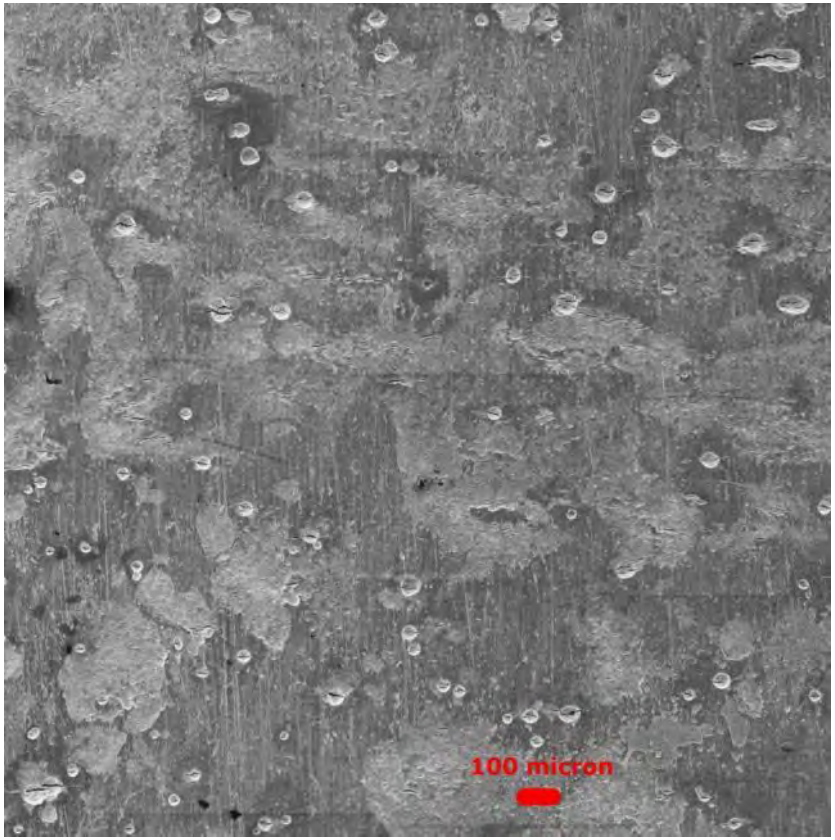


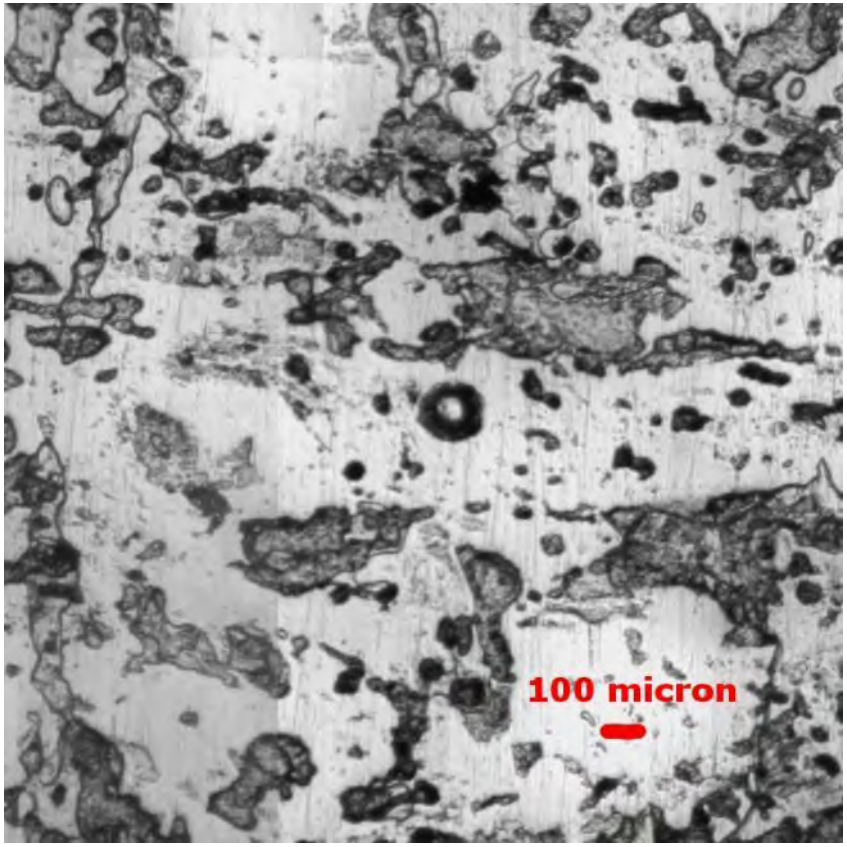
Crack growth rate A4T 320 MPa



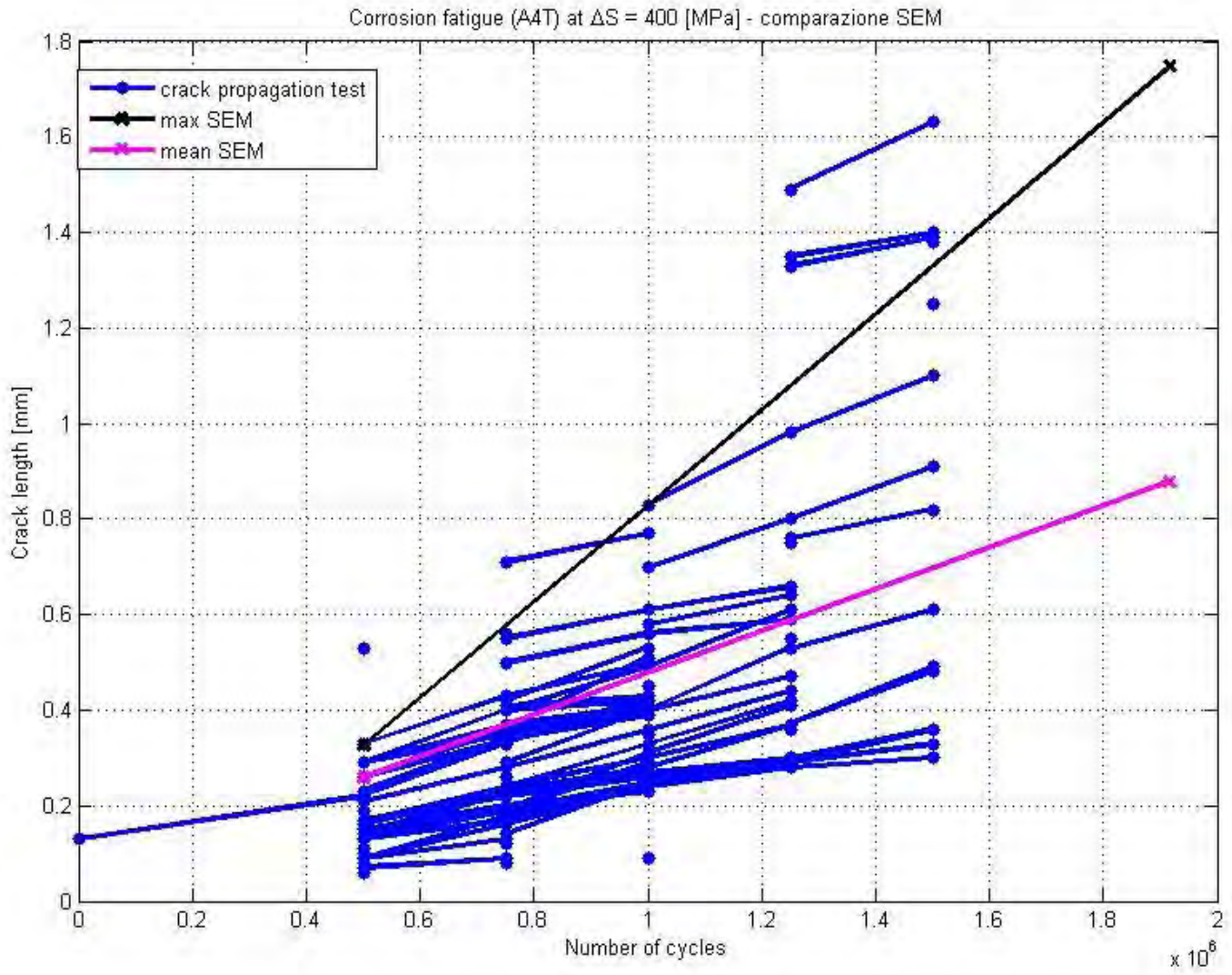
Interrupted test and crack propagation test 320 MPa

W55(6E5) – W30_interrupted(5E5) (320 Mpa)

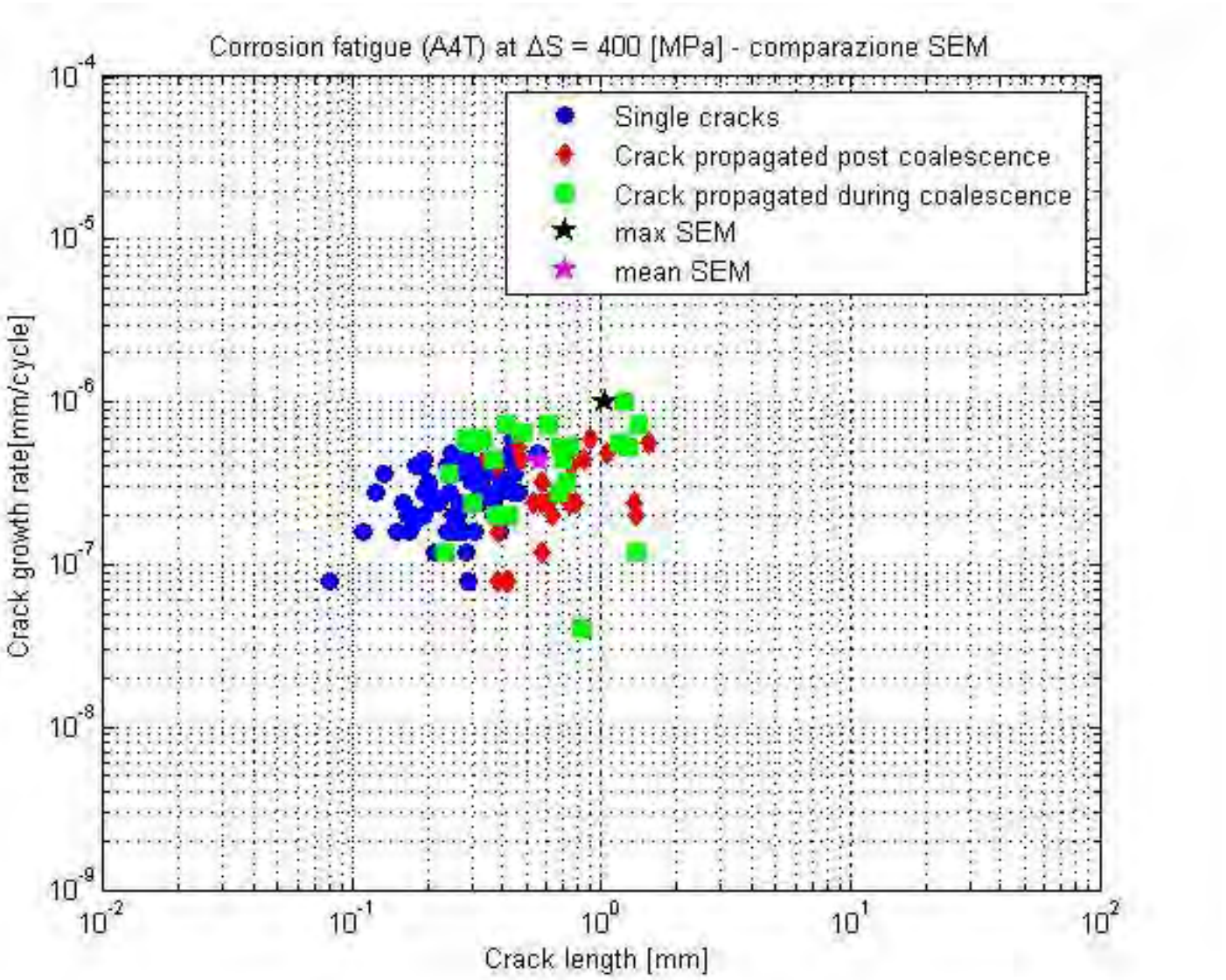




Propagation of single cracks A4T 400 MPa

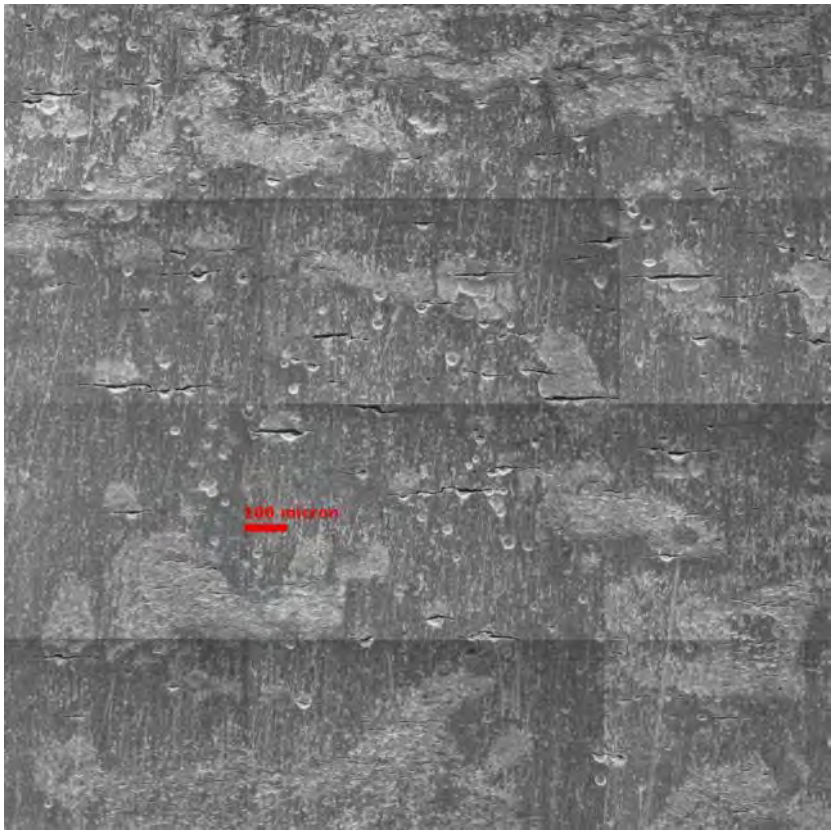


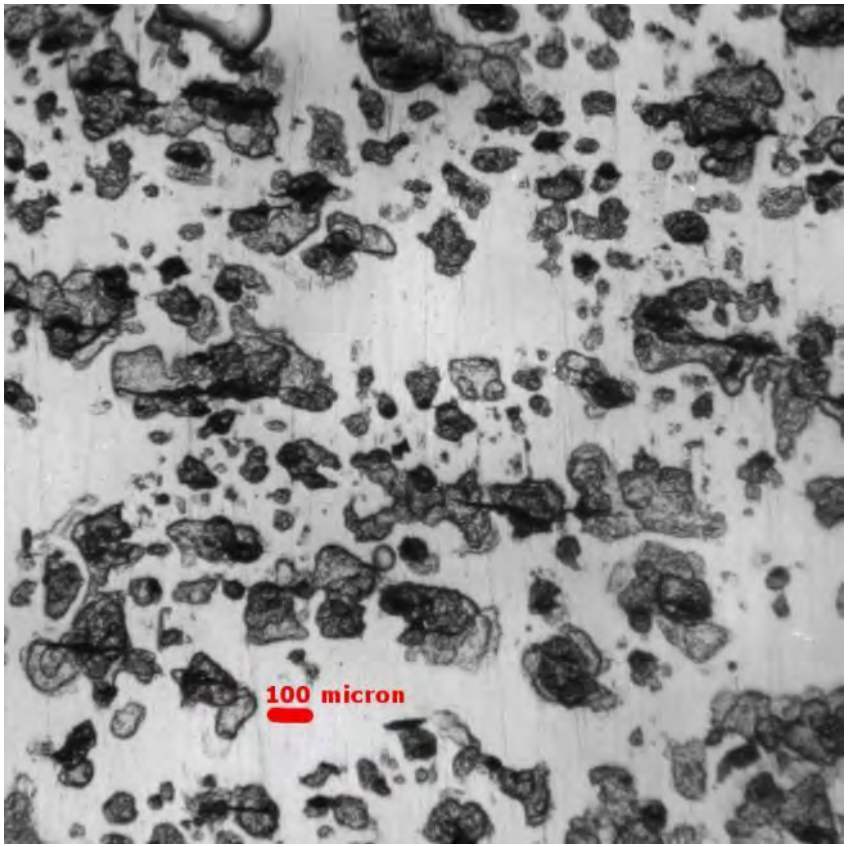
Crack growth rate A4T 400 MPa



Interrupted test and crack propagation test 320 MPa

W57(5E5) – W28_interrotto(5E5) (400 Mpa)





Conclusions

- The experimental tests have been completed
- The SN diagram for three materials has been obtained and show a similar a common digram for the compoared materials
- The trend of the crack propagation rate for different level of stress has been obtained for A1N and A4T
- The crack growth rate confirm the assumptions of the model developed within the T728 project and the model has been transferred to RCP
- The crack distributions at different stress level and percentage of life have been obtained
- For these results a total of 67 small scale experiments have been run

POLITECNICO DI MILANO





Prove Full-Scale

Summary of the full scale tests

Material	Max stress [MPa]	Cycles	Notes
A1T	Spectrum	$15\ 10^6$	Half life
A1T	160	$5\ 10^6$	Half life
A4T	160	$4.3\ 10^6$	About half life
A4T	120	$30\ 10^6$	End Life

Full scale test A4T $\Delta\sigma$ = 360 MPa

Stop for damage monitoring at:

1e6 cicli, 2.2e6 cicli, 4.3e6 cycles

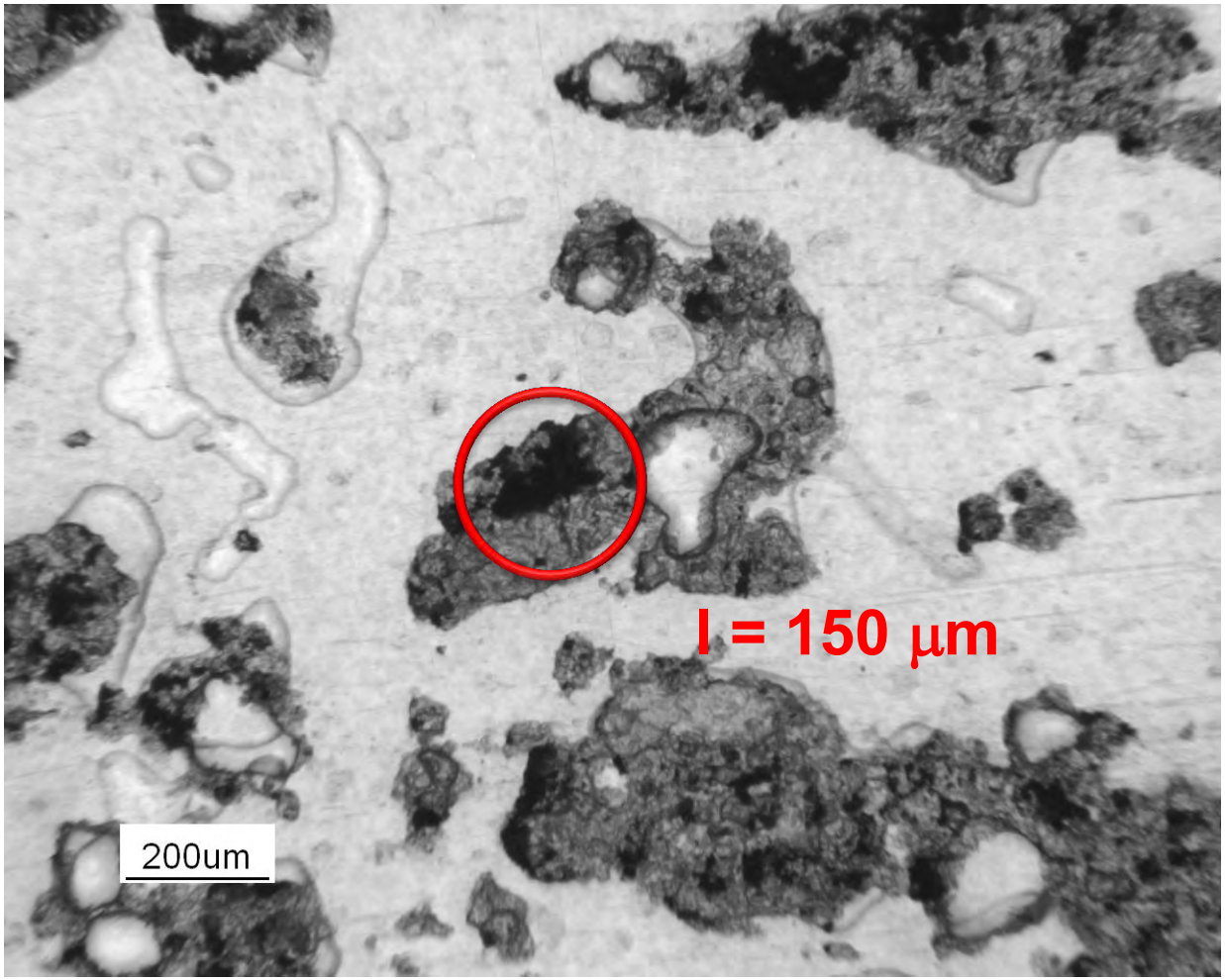
Stop at 1e6 cycles

Mechanical surface cleaning

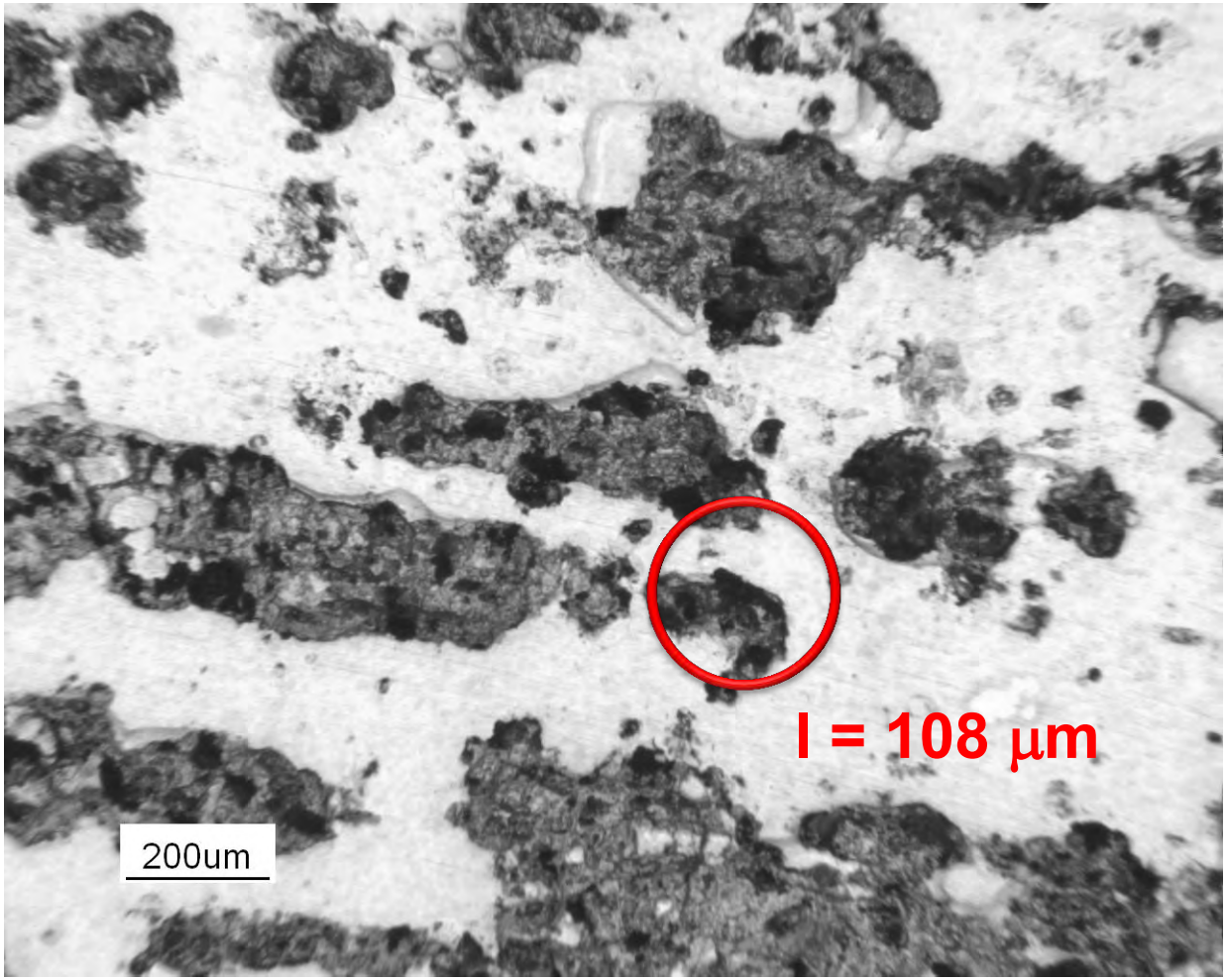
Before

After

Plastic replica 1e6 cicli 0°

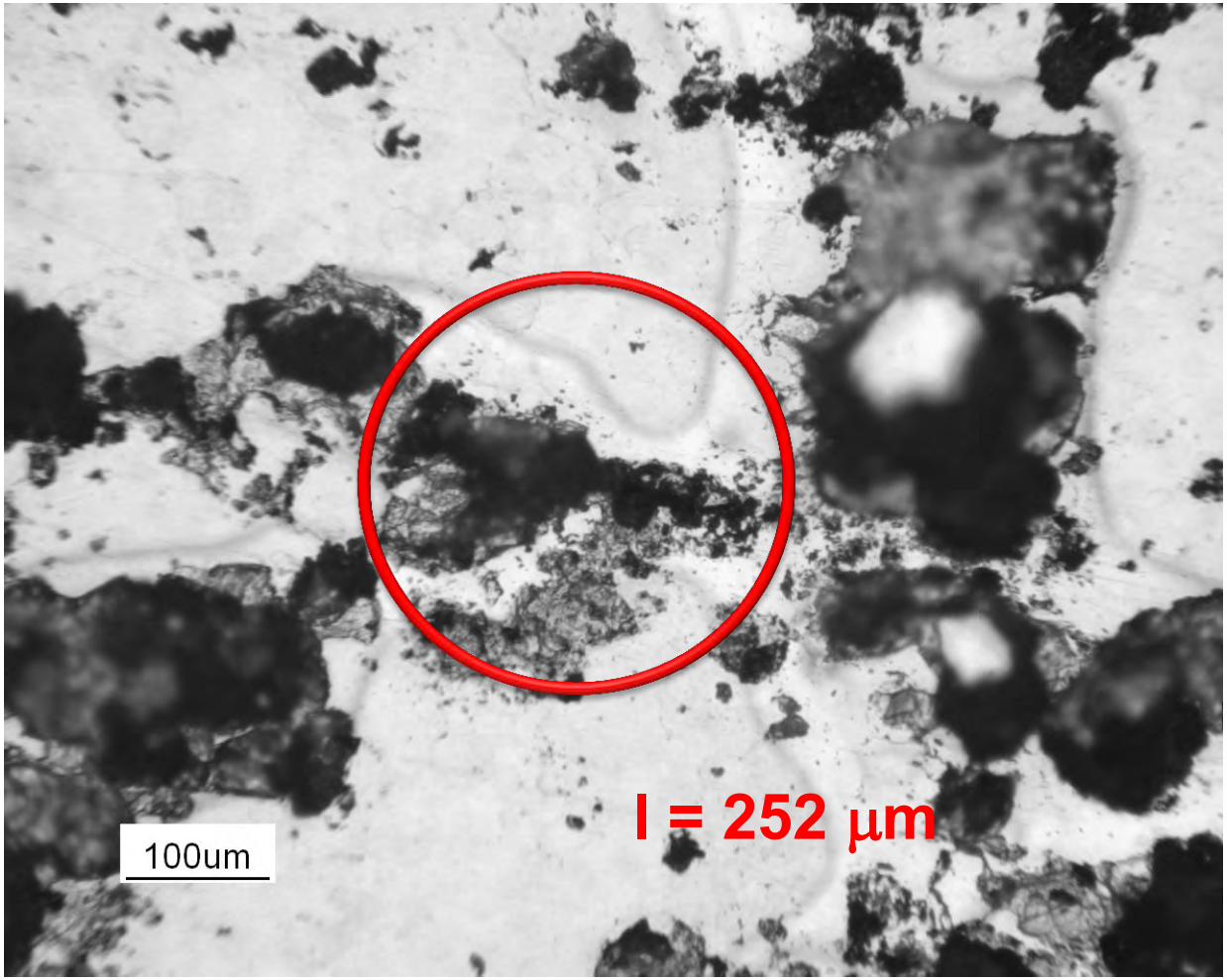


Plastic replica 1e6 cicli 0°



Small scale specimen, average crack lenght 200 micron

Plastic replica 2.2e6 cicli 0°



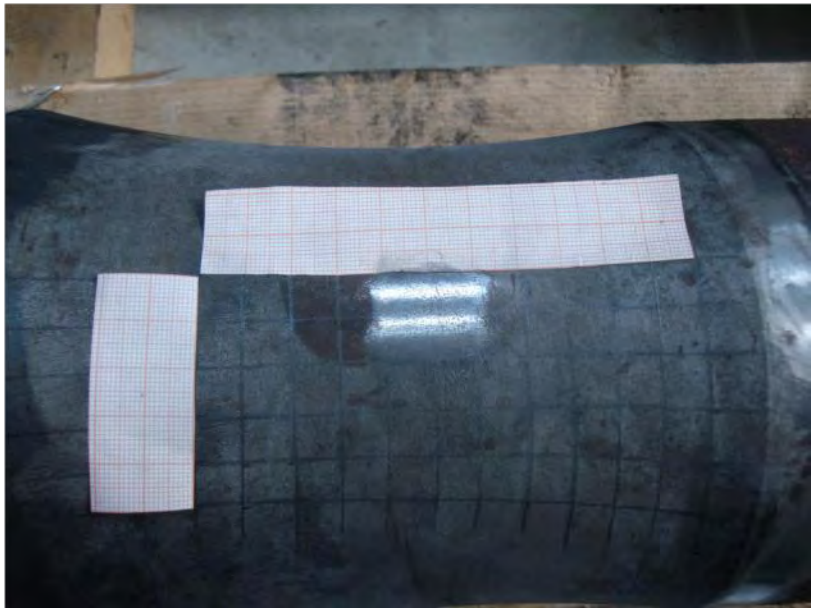
Small scale specimen, average crack lenght 160 micron at 1.5e6 cycles

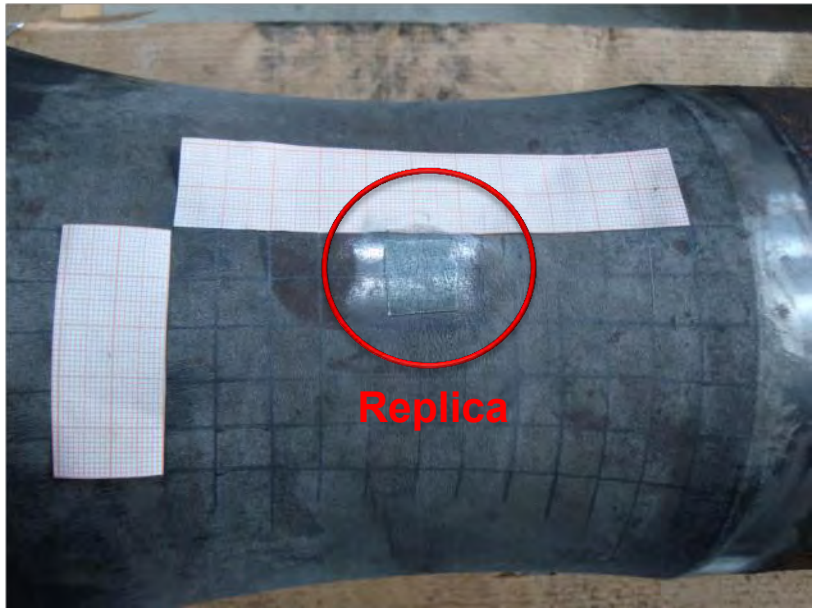
Chemical cleaning

Before

After chemical cleaning

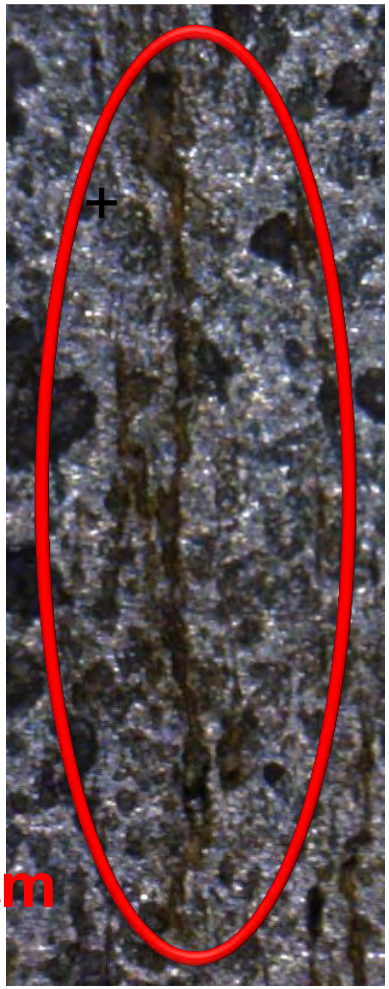
Mechanical cleaning– 4.317e6 cycles





After mechanical cleaning

Maximum crack a 4.317e6 cicli – 0deg



l = 1261 μm

TWI Optical device

l = 980 μm

Plastic replica

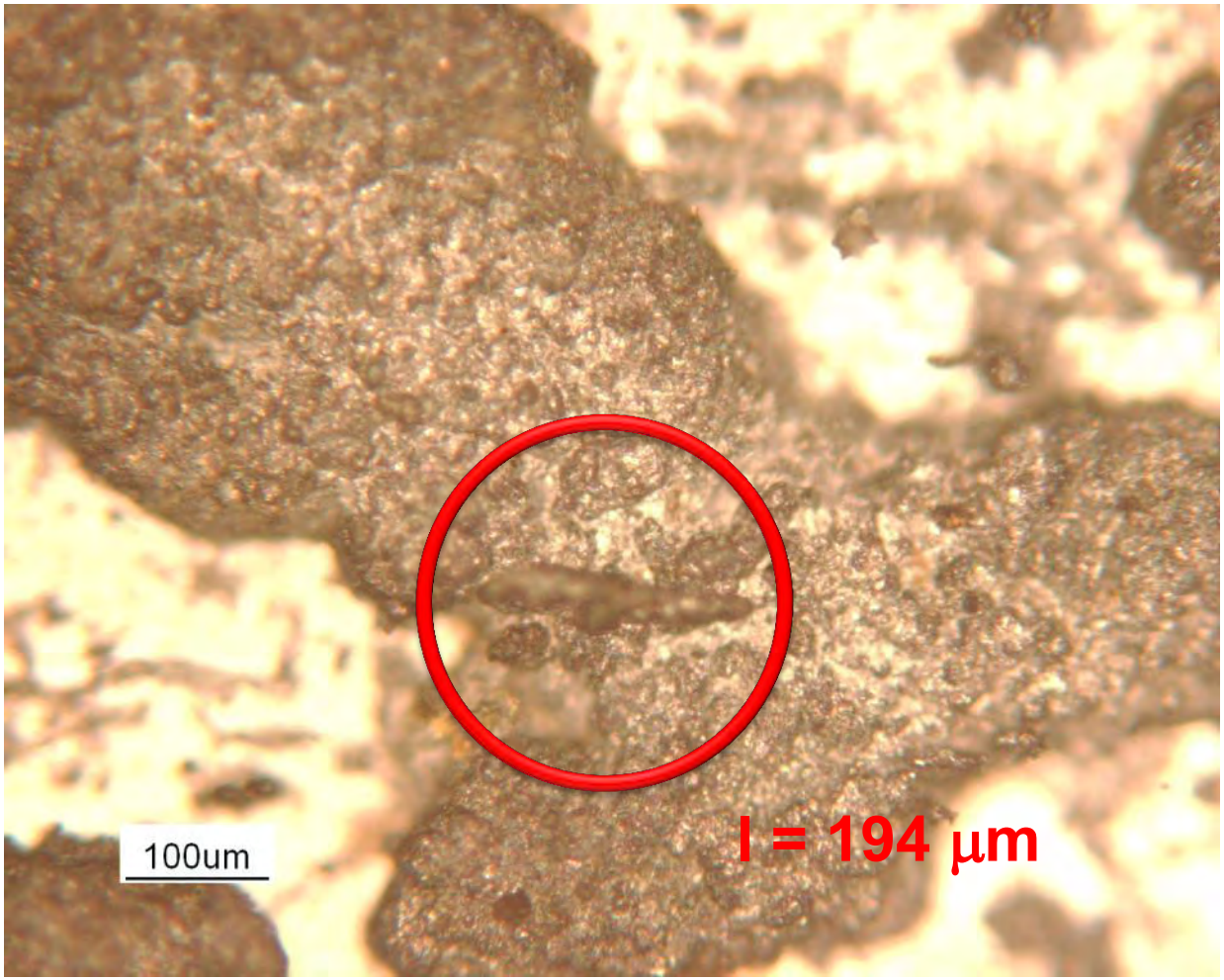
Full scale test A4T $\Delta\sigma$ = 240 MPa

Stop for damage monitoring at:

2e6 cycles, 4e6 cycles, 6e6 cycles, 12e6 cycles

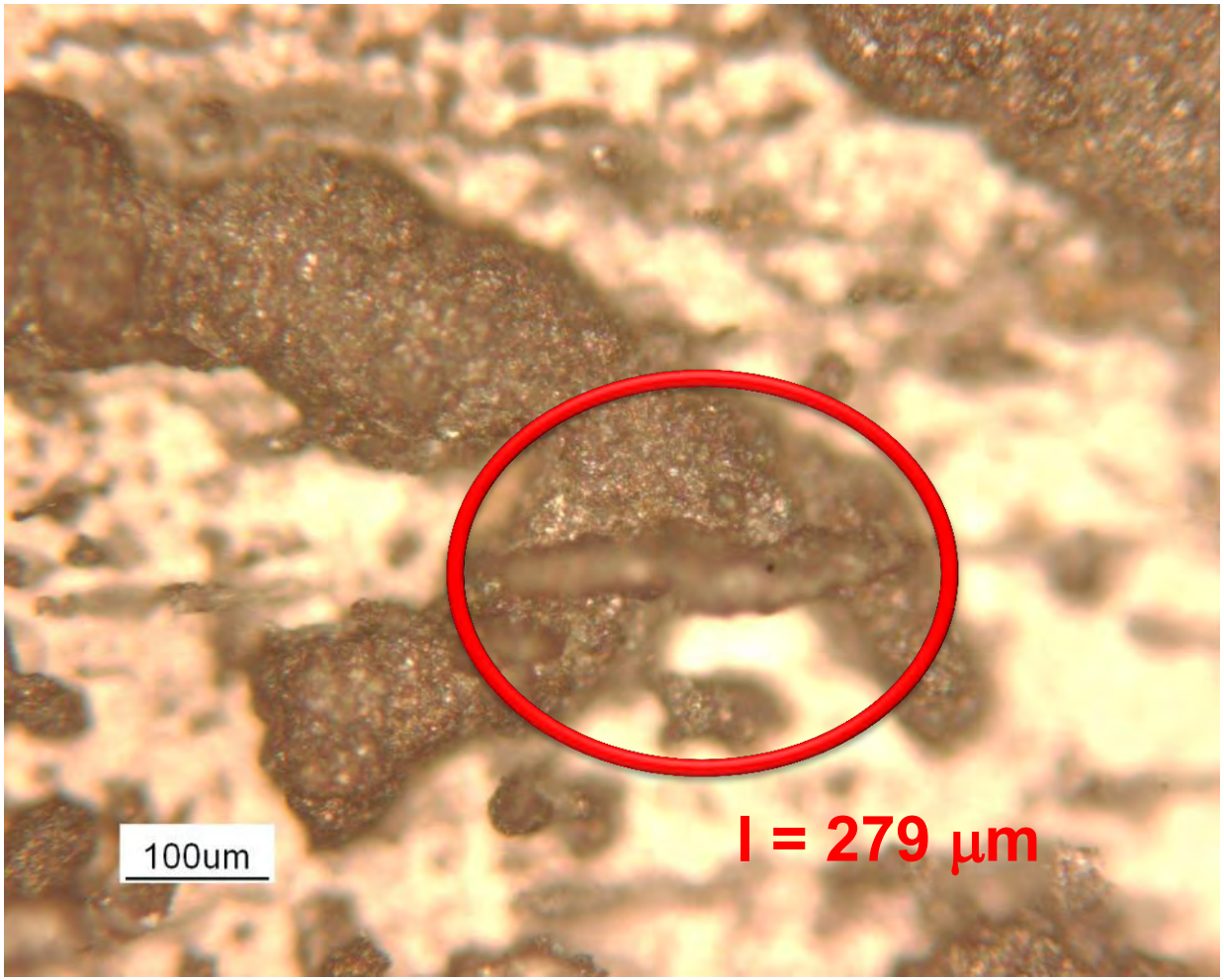
End life with very long crack at 30e6 cycles

Plastic replica 2e6 cycles

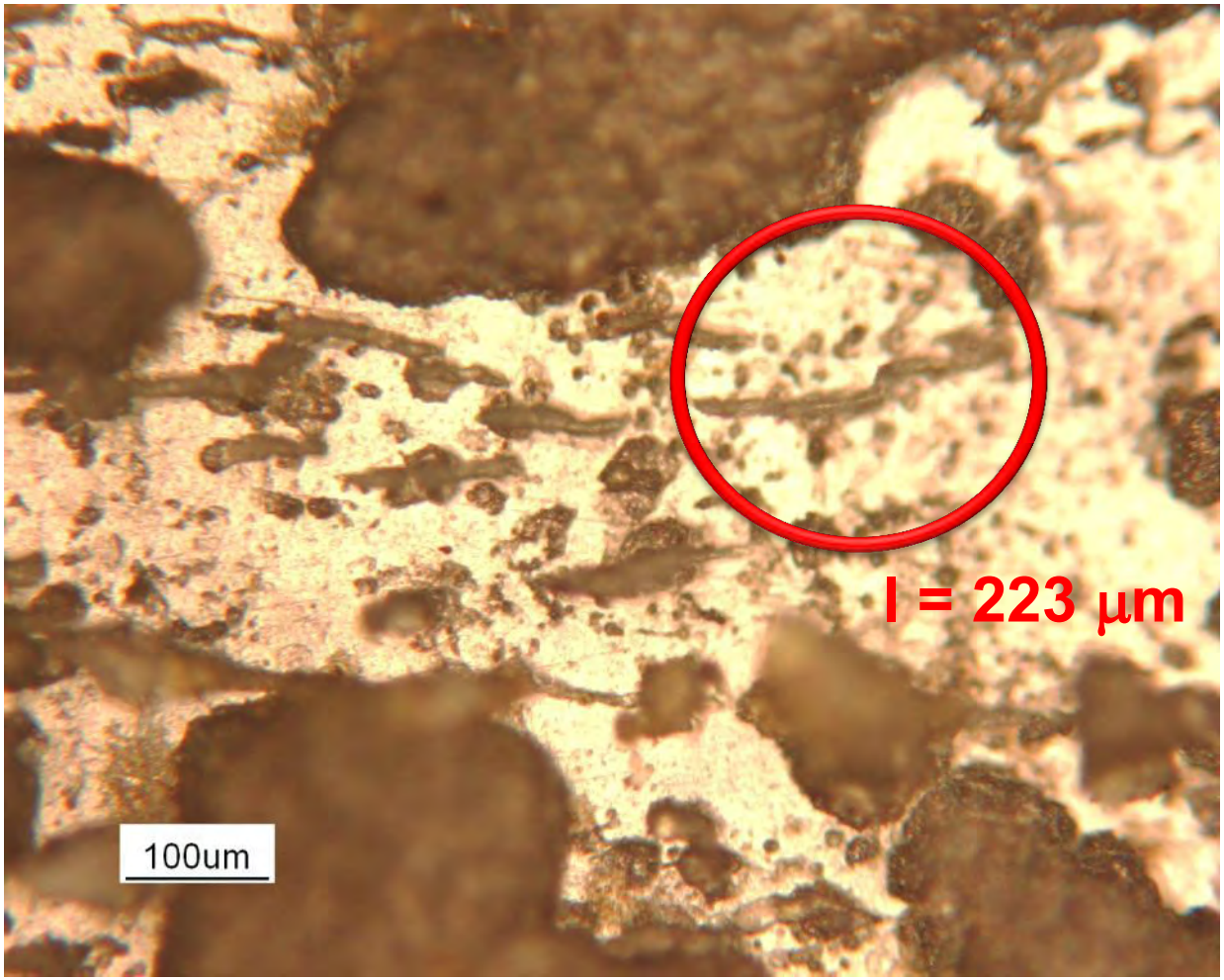


Small scale specimen, average crack lenght 160 micron

Plastic replica 2e6 cycles



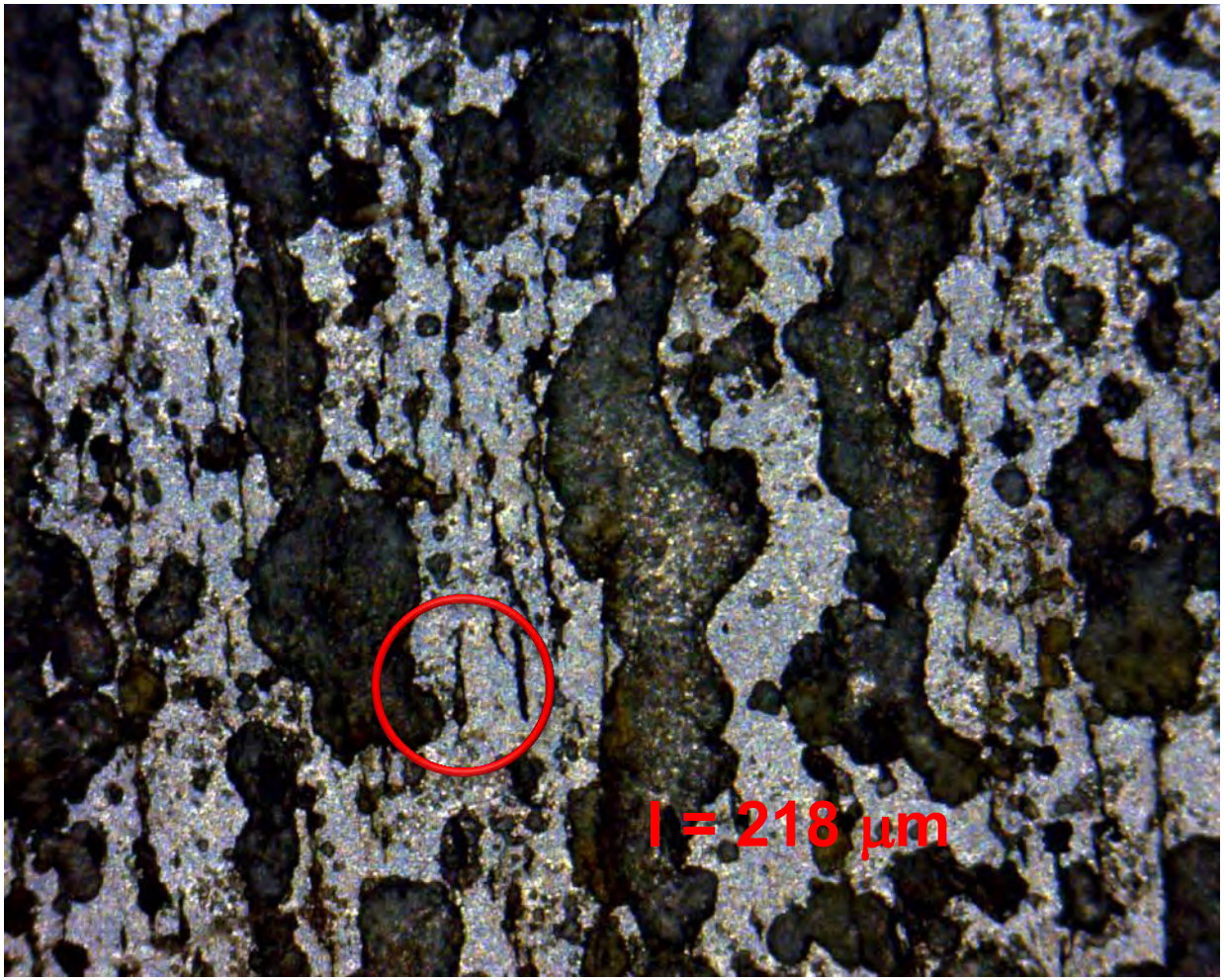
Plastic replica 2e6 cycles



TWI Digital Microscope – 2e6 cycles

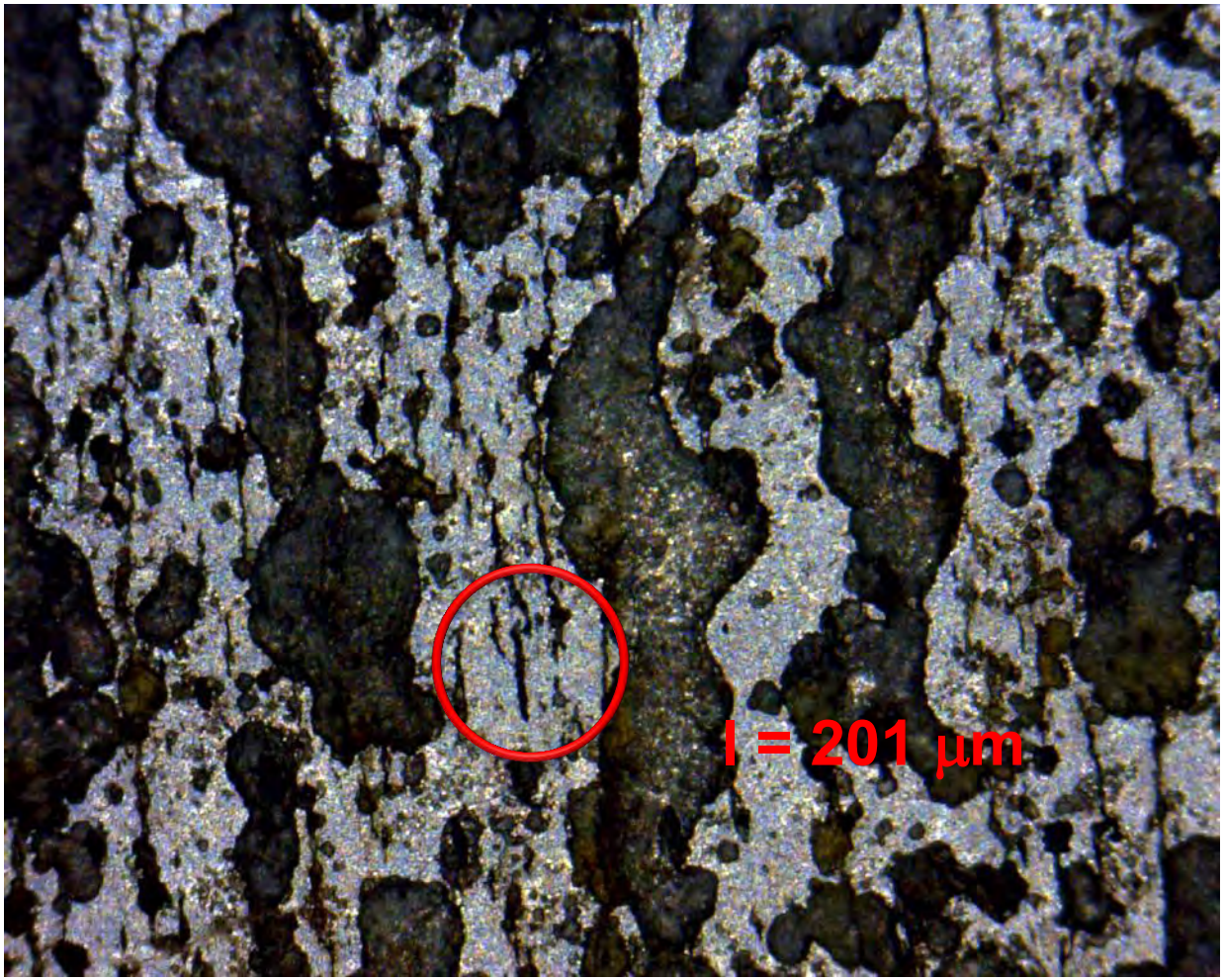
220x – Marker 1000 μm = 550 pixels

TWI Digital Microscope – 2e6 cycles



220x – Marker 1000 μm = 550 pixels

TWI Digital Microscope – 2e6 cycles

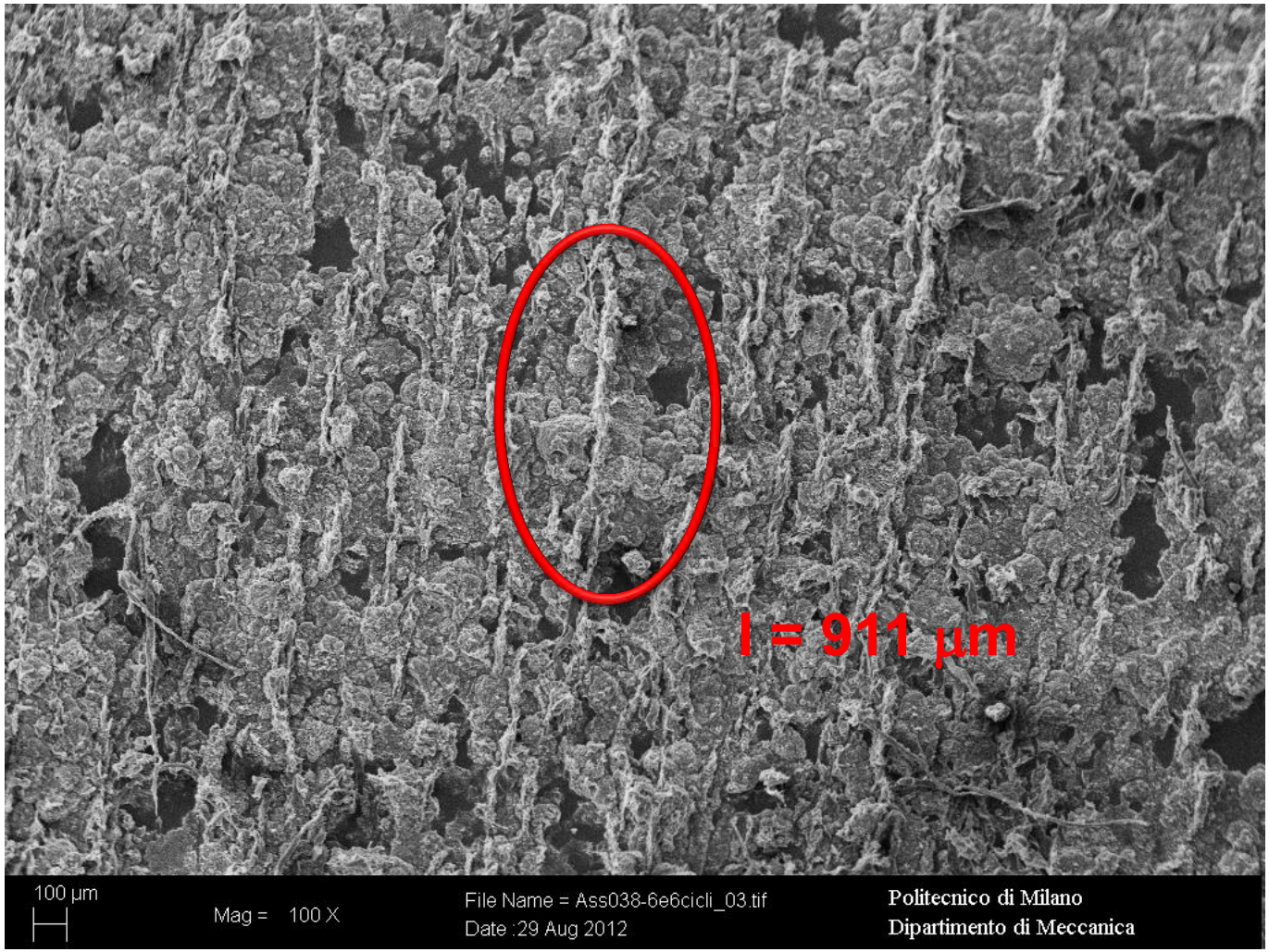


220x – Marker 1000 μm = 550 pixels

Plastic Replica 4e6 cycles

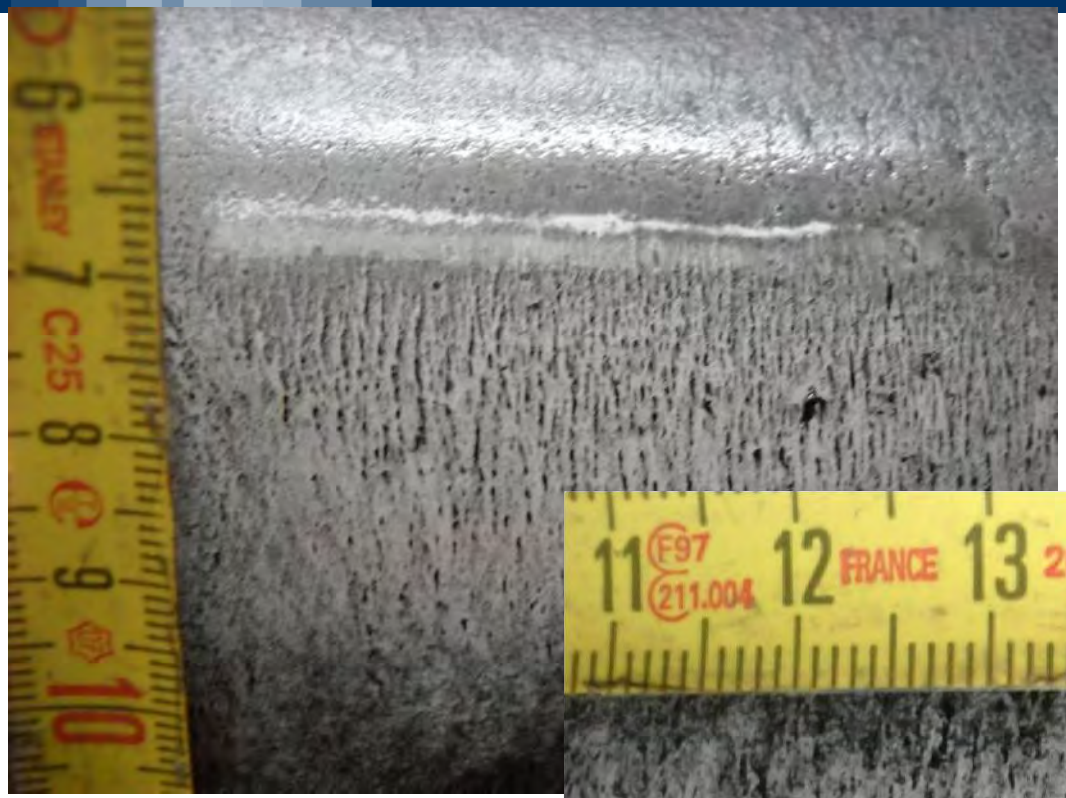
Small scale specimen, average crack lenght 1070 micron at 6e6 cycles

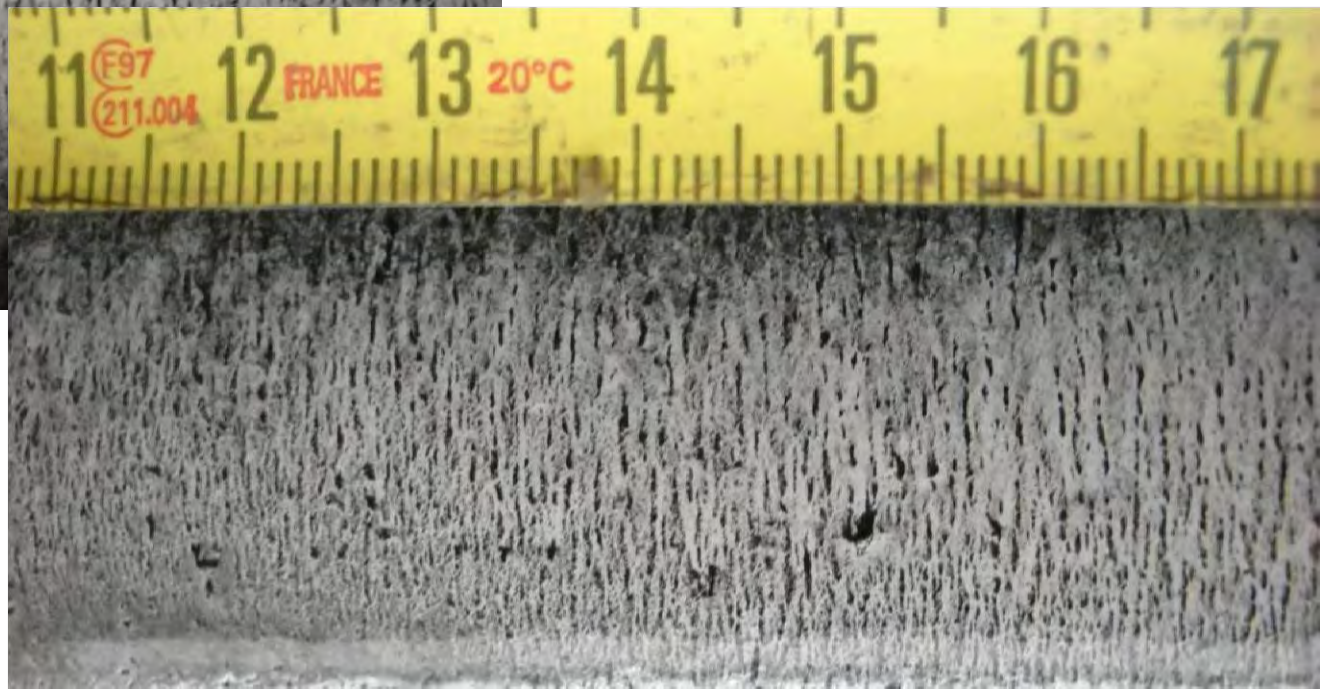
Assile 038 – Replica 6e6 cicli



Small scale specimen, average crack lenght 1070 micron at 6e6 cycles

End of the test 33 10^6 cycles





Conclusion

- Agreement between crack growth rate in small scale and full scale tests
- All the full tests experimental data are available for verification of the in progress corrosion fatigue model