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SCC CRACK INITIATION OF ALLOY 82 IN HYDROGENATED STEAM AT 400°C

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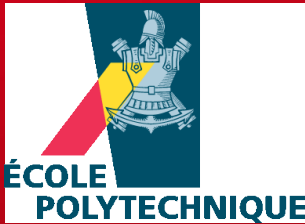
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⁴ IRSN, Institut de Radioprotection et de Sûreté Nucléaire

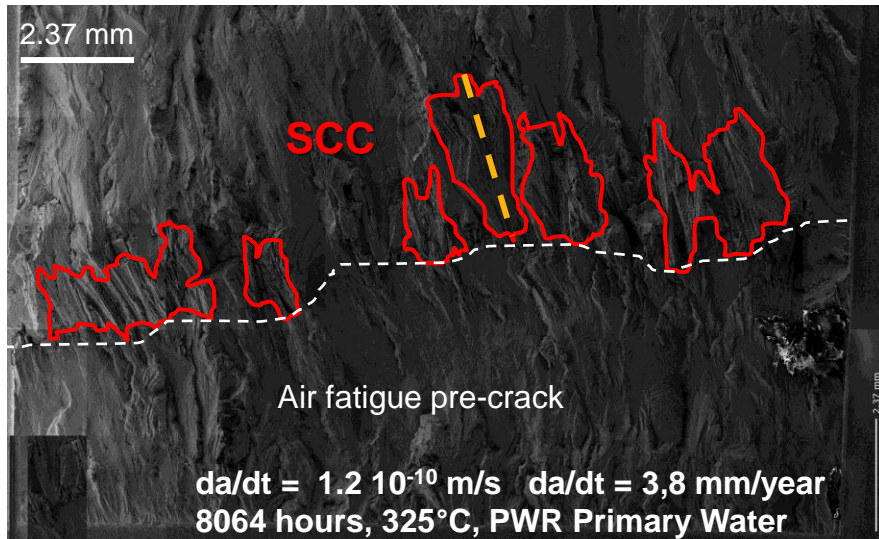
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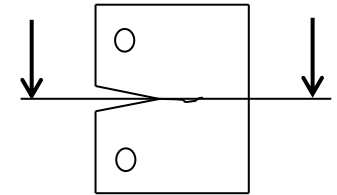
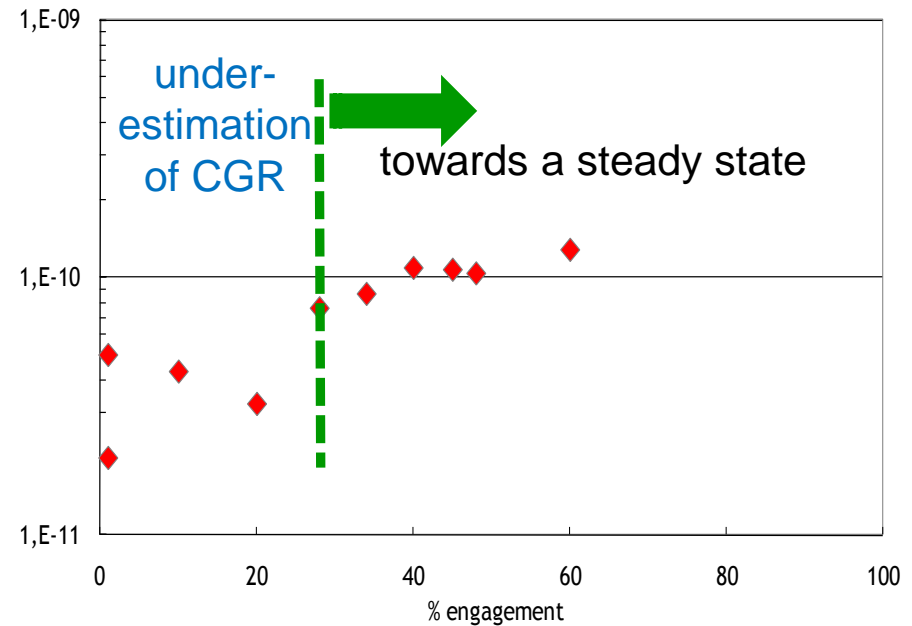


✓ SCC propagation tests [Guerre et al, 2011]

Alloy 82 CT specimen



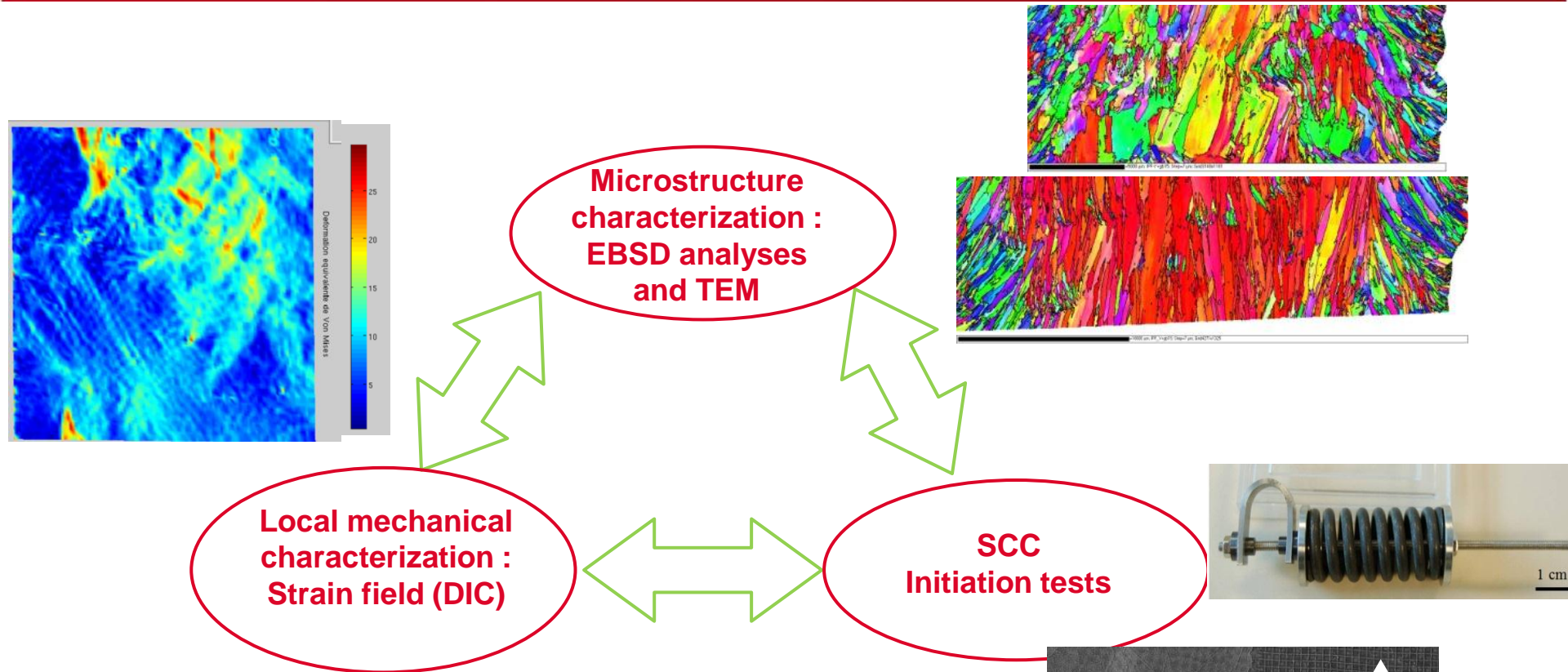
Maximum crack growth rate (m/s)



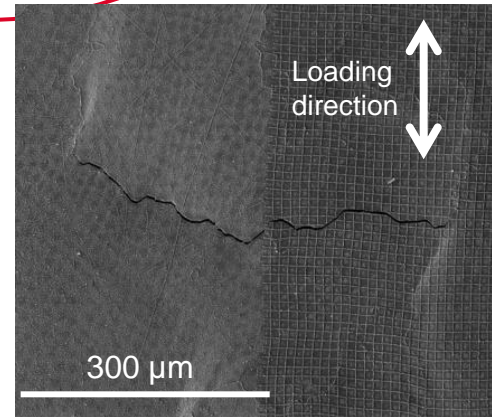
- Uneven crack front with pockets of IG cracks : % of engagement of the crack front is below 100%.
- Along susceptible grain boundaries, the crack growth rate can be very high (few mm/year).

→ **SCC behavior of welds is strongly related to their microstructure.**
→ **Life time depends on the initiation time.**

APPROACH AND AIM

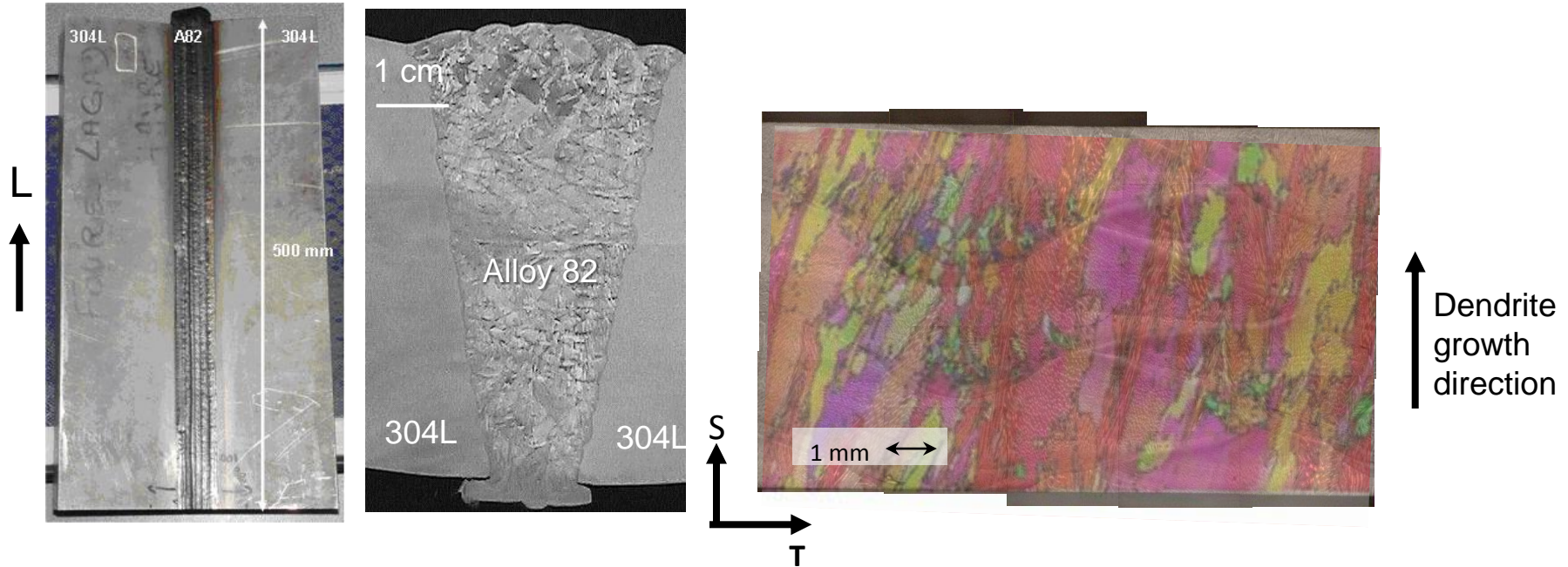


→ To identify which microstructural features associated with mechanical fields enable SCC initiation.



✓ Welds : Alloy 82 (no restraint)

- millimetric columnar grains made of several slightly misoriented dendrites



✓ Chemical composition of Alloy 82 (weight%)

	C	S	Si	Mn	Ni	Fe	Cu	Cr	Nb	Ti	P	Co	Mo	O
RCC-M requirements	<0.1	<0.015	<0.5	2.5/3.5	>67	<3	<0.5	18-22	2/3	<0.75	<0.03	<0.1	-	-
Alloy A	0.025	<0.001	0.07	2.57	71.7	3.07	<0.01	19.12	2.41	0.1	0.004	0.04	0.02	0.0016
Alloy B	0.014	0.017	0.17	2.88	72.9	2.3	<0.01	18.15	2.83	<0.01	0.002	0.01	0.05	0.067

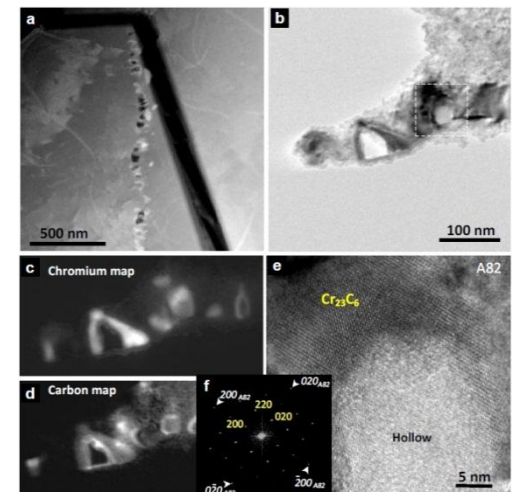
Butt weld reference	Chromium content	Carbon content	Metallurgical state	Welding process
Alloy A (AW)	19%	0.025%	As-Welded	Gas Tungsten Arc Welding (GTAW)
Alloy A (HT)	19%	0.025%	Heat-Treated ¹ (7 hr @ 600°C)	Gas Tungsten Arc Welding (GTAW)
Alloy B (AW)	18%	0.014%	As-Welded	Flux Cored Arc Welding (FCAW)

¹ similar to the in-service stress relief treatment

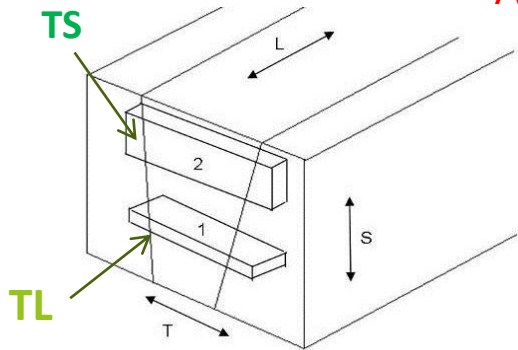
□ Effect of the heat treatment on the precipitation:

- Alloy A : intergranular chromium carbides precipitation (Cr_{23}C_6)
- Alloy B : no IG chromium carbides

A82 19% Cr
Heat treated

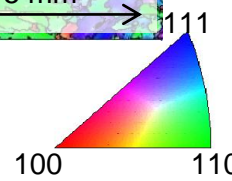
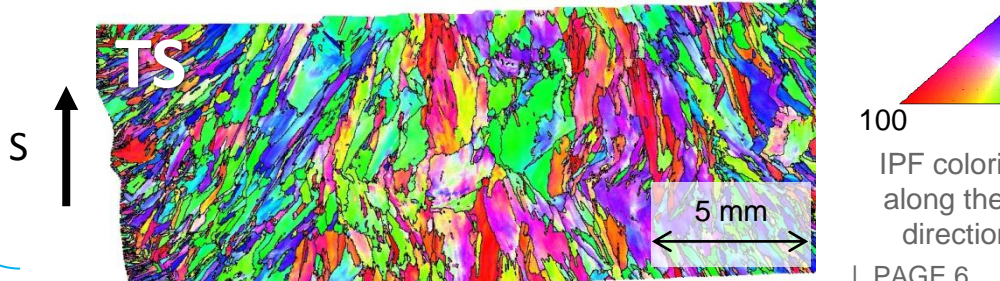
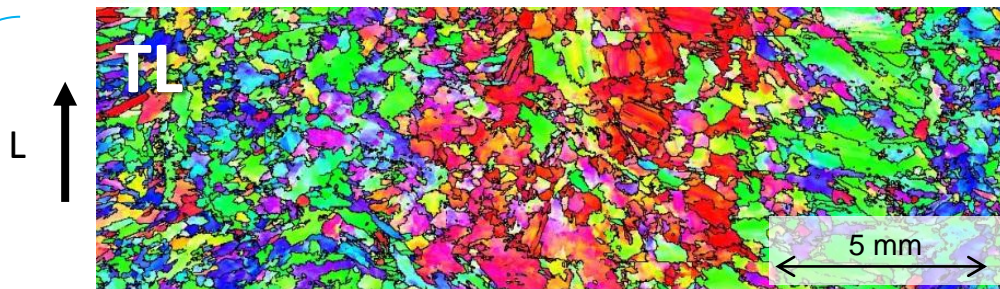
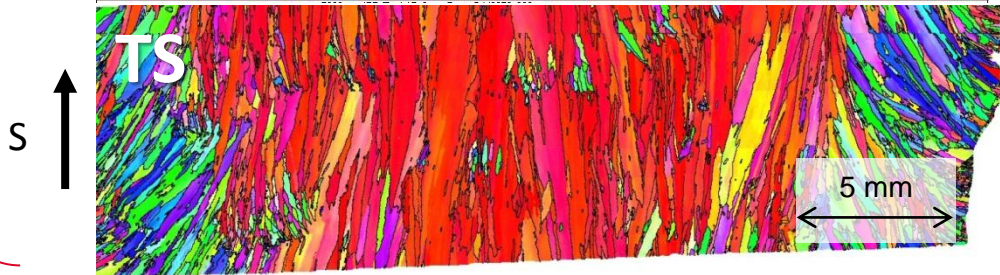
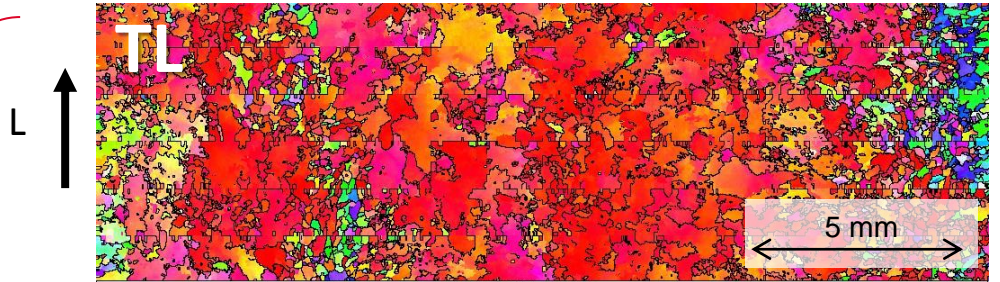


✓ EBSD analyses



Alloy B
AW FCAW

Alloy A
AW GTAW



IPF coloring
along the S
direction

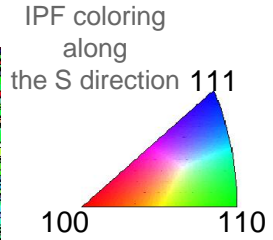
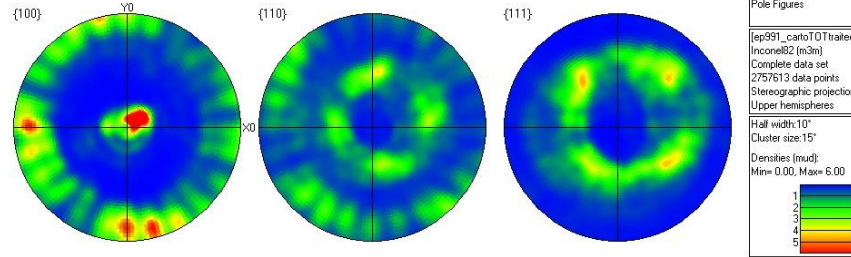
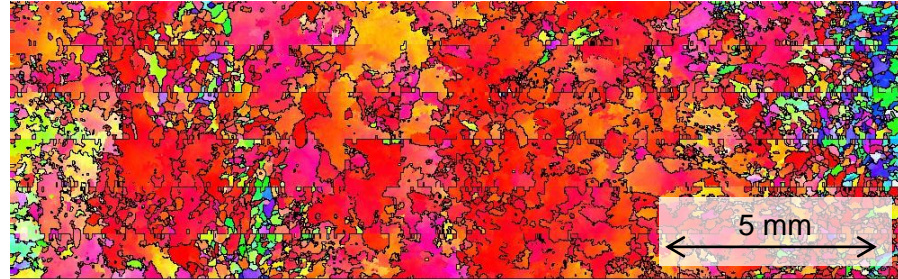
- ✓ Large grain size (mm) : macroscopic microstructure
- ✓ Heterogeneous grain size
- ✓ Nearly equiaxed shape (TL)
- ✓ Cristallographic texture isn't the same for the two alloys and depends on the welding process.

✓ EBSD analyses : crystallographic orientation

Alloy B

Cubic and transversal isotropic texture with [001] // dendrite growth direction

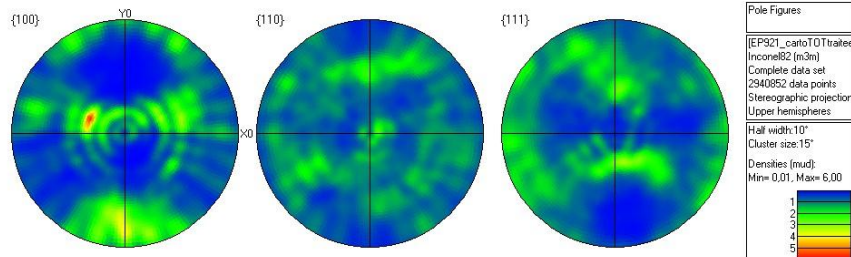
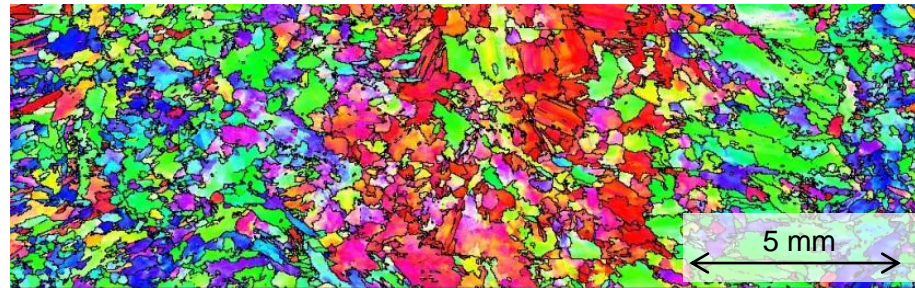
TL ↑
L



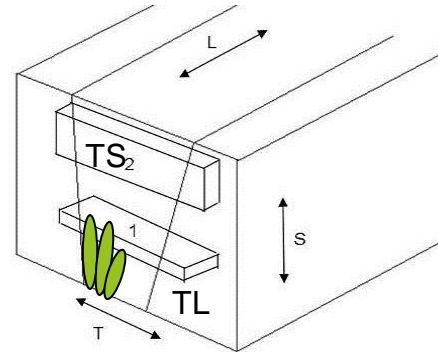
Alloy A

No crystallographic texture

TL ↑
L



→ U-bends specimen in hydrogenated steam



dendrites

- Hydrogenated steam :

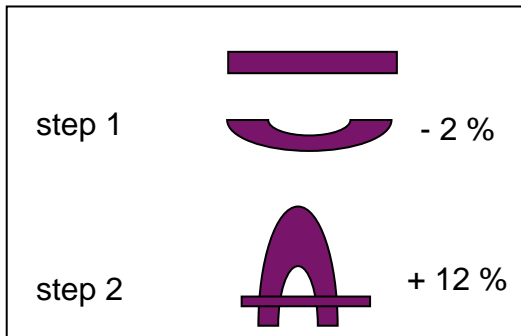
Temperature	400 °C
Total pressure	188 bar
Hydrogen partial pressure	0.7 bar

- Strain fields are measured using gold grids and Digital Image Correlation.

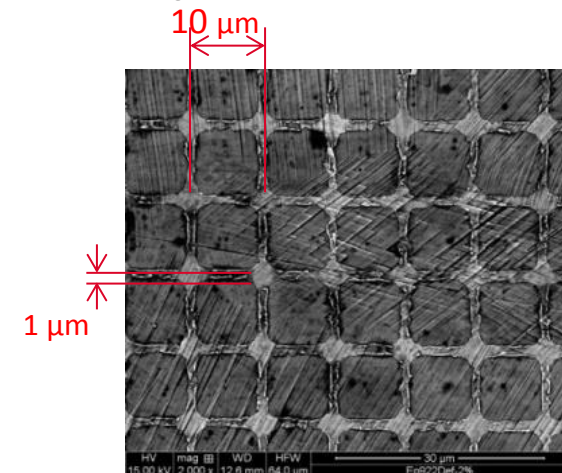
- Direct loading path or complex loading path:

0 % → +12%

0% → -2% → +12%

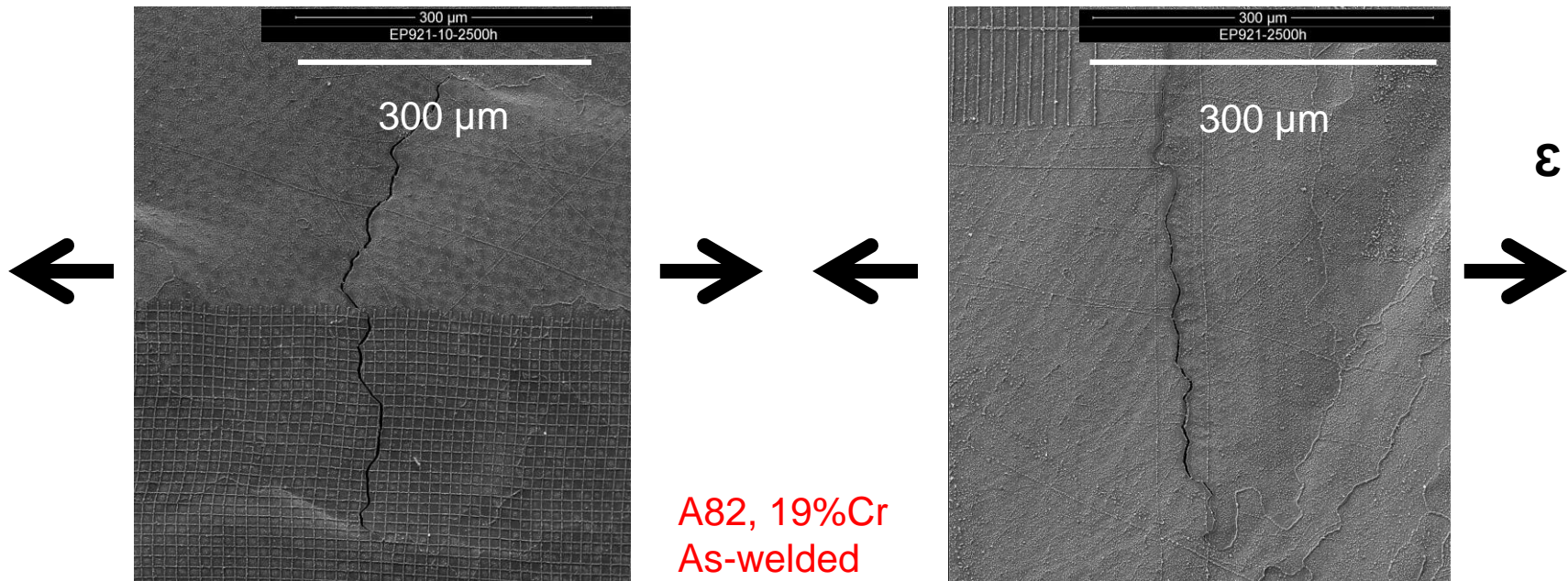


- Test time :
500 hr, 1500 hr, 2500 hr
and 3500 hr.



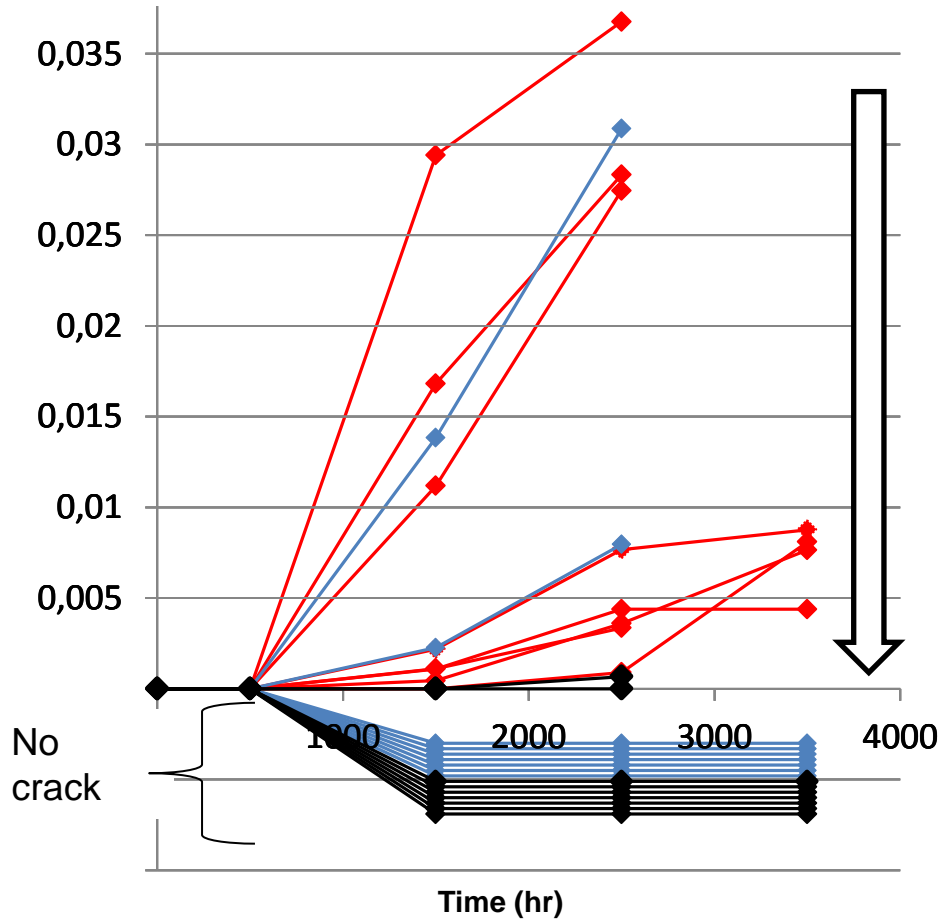
✓ SCC susceptibility.

- ✓ No crack after 500 hr in hydrogenated steam at 400°C.
- ✓ First cracks are observed after 1500 hr for the as-welded alloy and after 2500 hr for the heat-treated alloy (only one shallow crack).
- ✓ Cracks are intergranular.
- ✓ Cracks are observed inside and outside gold grids (used for DIC and strain field measurements) : the cracks are not induced by the grids.
- ✓ Most of the cracks are perpendicular to the loading direction.



INITIATION TEST : RESULTS

Number of cracks / number of perpendicular grain boundaries



- Alloy A : A82 19%Cr, GTAW, as-welded
- Alloy A : A82 19%Cr, GTAW, heat-treated
- Alloy B : A82 18%Cr, FCAW, as-welded

The number of cracks increases with time.

Alloy A (AW) is less susceptible than Alloy B (AW).

Alloy A (HT) is less susceptible than Alloy A (AW).

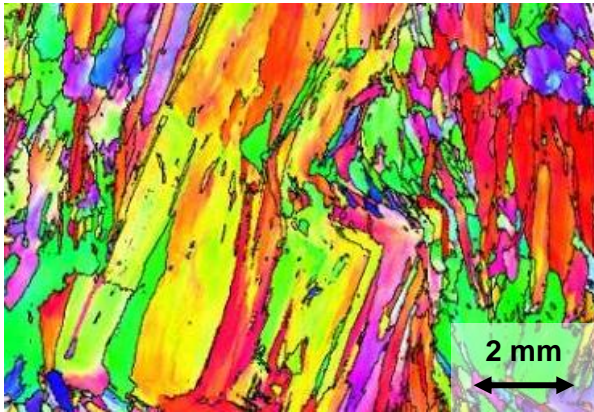
Number of cracked specimen.

8 specimen were removed.

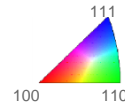
Time (hr)	500	1500	2500	3500
Alloy A AW	0/7	2/7	2/7	0/5
Alloy A AW	0/2	0/2	0/2	0/2
Alloy A HT	0/7	0/7	1/7	0/5
Alloy A HT	0/2	0/2	0/2	0/2
Alloy B AW	0/6	5/6	6/6	2/2
Alloy B AW	0/2	2/2	2/2	2/2

INFLUENCE OF THE MICROSTRUCTURE

Alloy A : A82, 19%Cr GTAW, as-welded

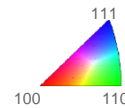
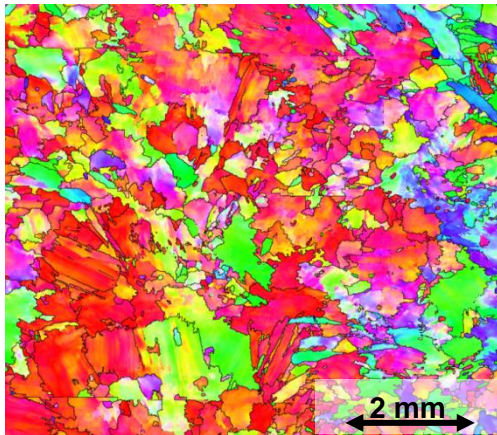
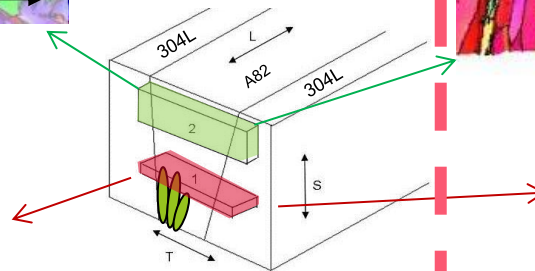


Direction de sollicitation
←→

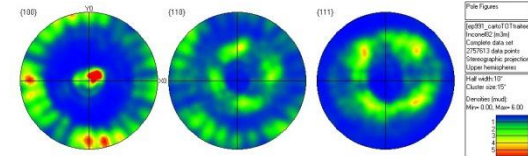
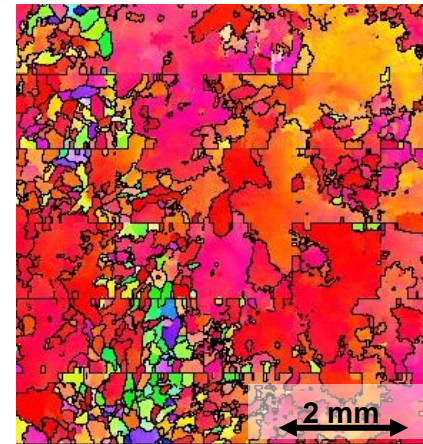


IPF
colouring
along the Y
axis

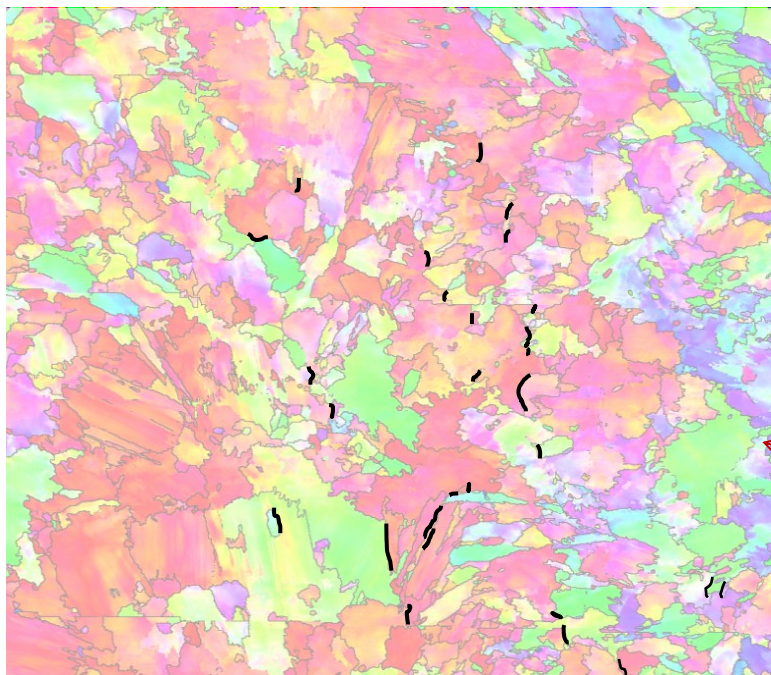
Alloy B: A82, 18%Cr FCAW, as-welded



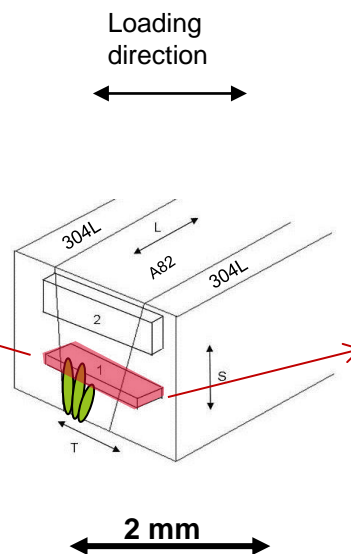
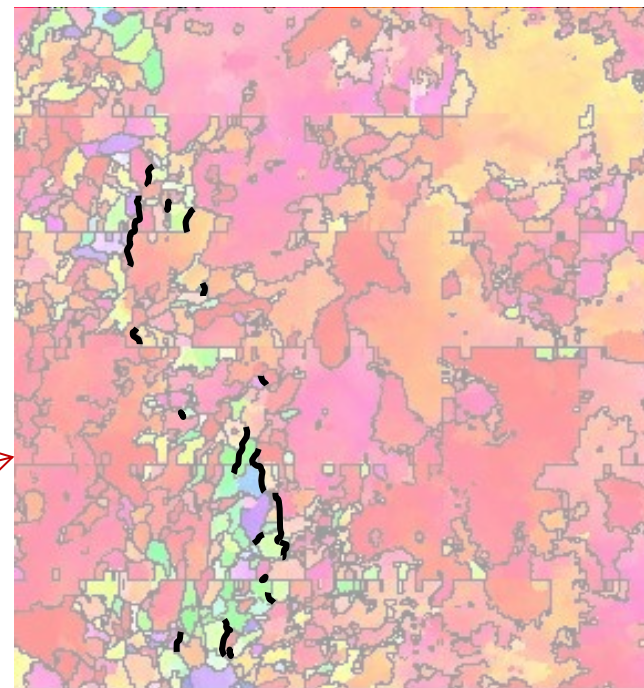
IPF
colouring
along the Z
axis



Alloy A : A82, 19%Cr GTAW, as-welded



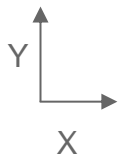
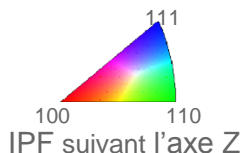
Alloy B: A82, 18%Cr FCAW, as-welded



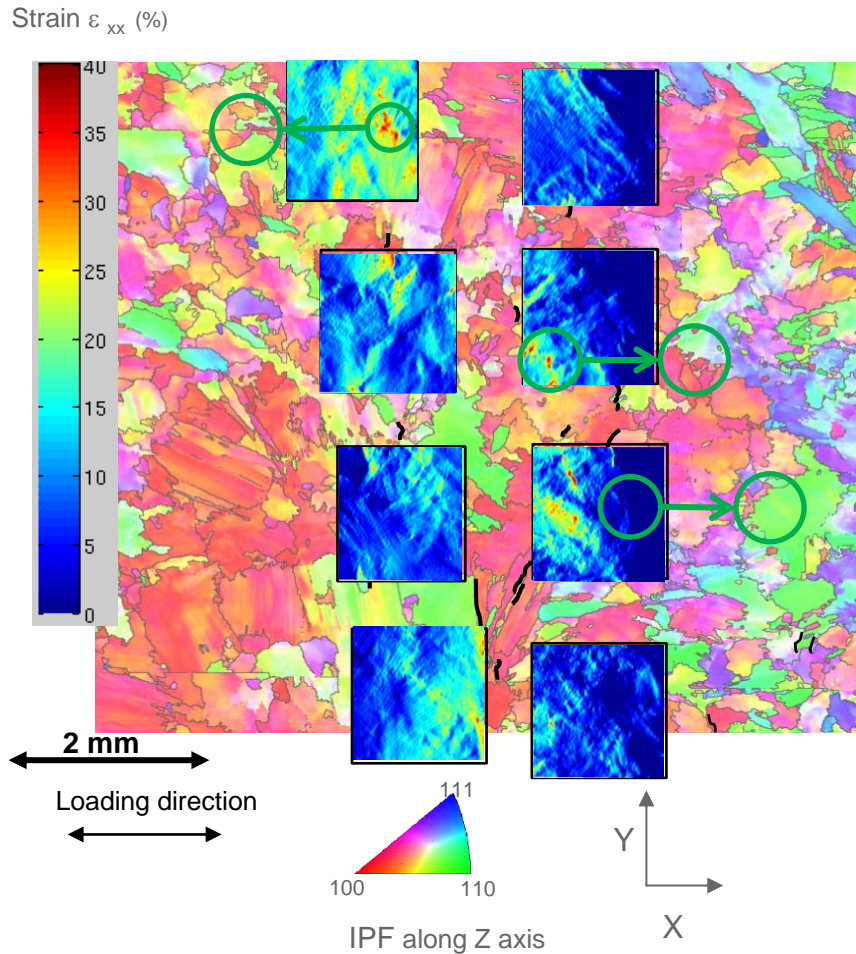
→ Cracks on **random grain boundaries**.

→ **No preferred grain orientation** next to cracked GB.

→ Most of the cracked GB are located **in zones containing small grains** (roots of the weld passes) : no segregation has been observed (SIMS, electron probe microanalyser).



Alloy A : A82, 19%Cr GTAW, as-welded

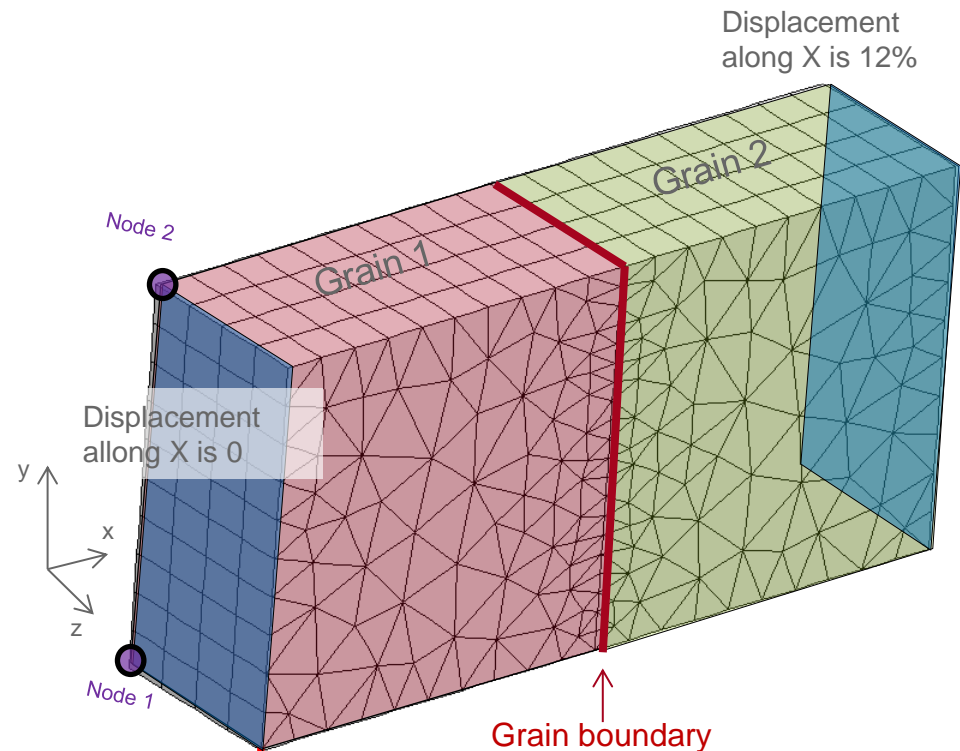


Average Von Mises strain for each grid

	16 %	5,2 %	
	10,4 %	4,6 %	
	8 %	5,4 %	
	11 %	4,8 %	

- Heterogeneous strain fields are measured by digital image correlation.
- No direct correlation between strain localization and crack initiation¹.
- **Finite element simulations** have been carried out in order to determine normal **stress fields** along cracked and uncracked grain boundaries.

→ Simulation of stress fields by finite elements are performed on bicrystals simulating one GB in the case of 16 cracked grain boundaries and 13 uncracked grain boundaries.



→ Crystallographic orientations are extracted from the EBSD characterizations.

→ Crystallographic law (octaedic elasto-viscoplastic law)¹

$$\dot{\gamma} = \left\langle \frac{(\sigma - X) - R}{K} \right\rangle^n$$

$\dot{\gamma}$: shear rate

σ : critical resolved shear stress

X : kinematic hardening

R : isotropic hardening

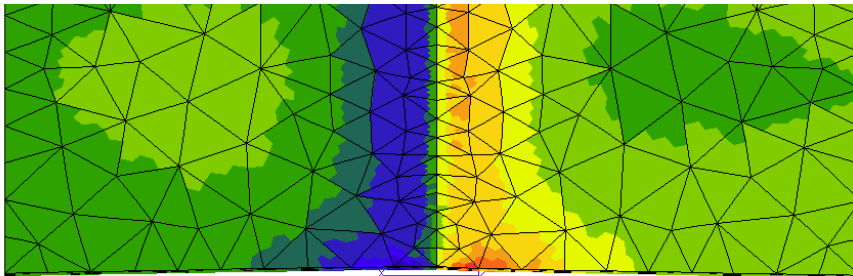
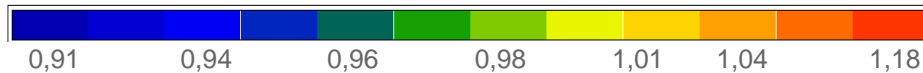
K and n : Norton law's parameters

→ Boundary conditions :
a displacement along X is applied

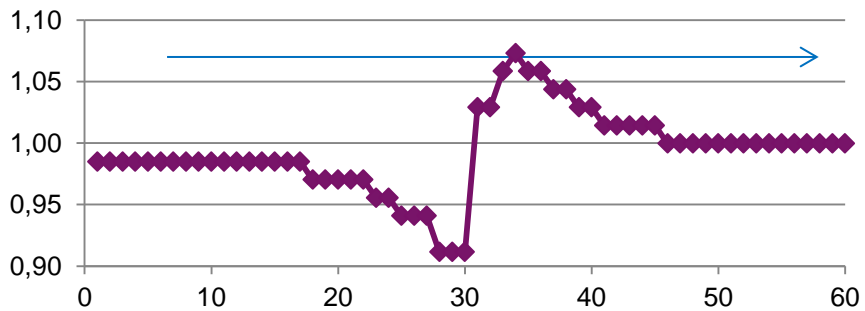
→ First step : a macroscopic deformation of 12 % is applied on true crystallographic orientations.

→ Results : maximum normal stress

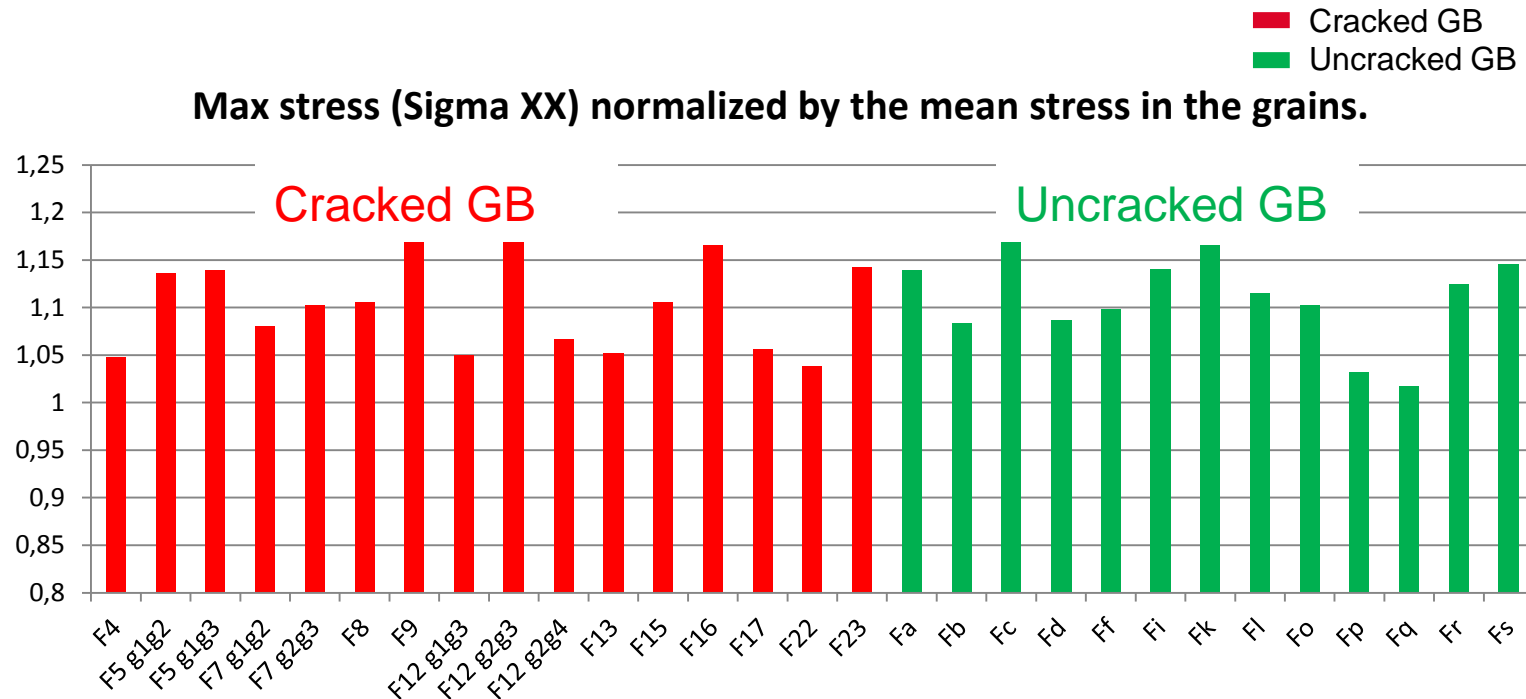
Max stress (Sigma XX) normalized by the mean stress in the grains.



→ Stress localisation close to the grain boundary in all cases (cracked and uncracked GB).



→ Comparison between cracked and uncracked grain boundaries.



→ The stress is not systematically higher for cracked grain boundaries.

→ The **strain field** (measured by DIC) should also be used **as a boundary condition** : both experimental crystallographic orientation and strain fields -> is the maximum normal stress a criteria to predict cracked GB ?

- SCC initiation test:
 - **Alloy 82 is susceptible to SCC** initiation in hydrogenated steam at 400°C : first cracks are observed **after 1500 hr.**
 - The **thermal treatment** (similar to the in-service stress relief treatment) can decrease the susceptibility to SCC. In this study, it is probably due to the **formation of intergranular chromium carbides.**
 - As – welded Alloy B is more susceptible to SCC than as-welded Alloy A : not the same chemical composition and not the same crystallographic texture (welding process is different). No IG chromium carbides for both alloys.

- Correlations between microstructure / strain fields and SCC :
 - **Crystallographic orientations and strain localization are not sufficient parameters to predict susceptible grain boundaries.**
 - Most of the cracks are located **in zones with the smallest grains** (roots of the weld passes) **-> chemical analysis are in progress**

- Future **FE simulations** will take into account **both the strain fields measured by digital image correlation and the crystallographic orientations** : critical normal stress to discriminate between cracked and uncracked GB ?

- *Which one of those parameters will be at the first order of magnitude ?*