SCC Crack initiation in nickel based alloy welds in hydrogenated steam at 400°c

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DE LA RECHERCHE À L'INDUSTRIE

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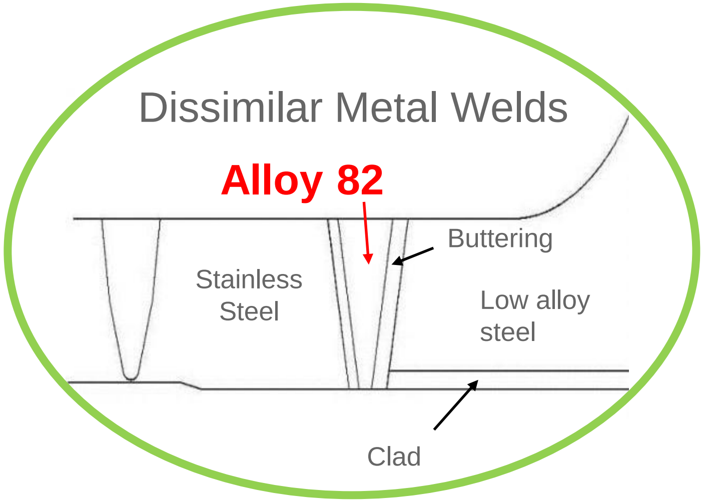
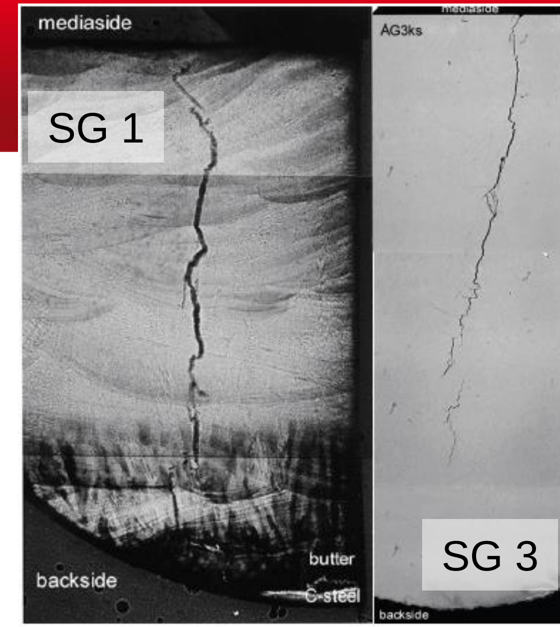
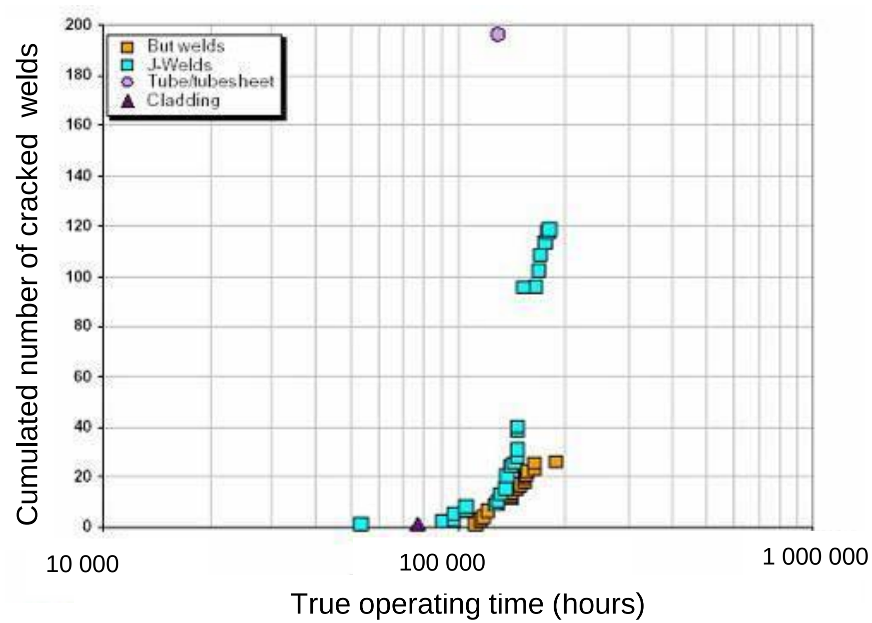
Context

→ Alloy 82 used in Dissimilar Metal Welds
→ Focus on the primary loop of Pressurized Water Reactor



SCC cracks in Alloy 82 welds in J-Groove weld of Ringhals Steam Generator [Efsing2005]





- In France, all DMW are stress-relieved
- Alloy 82 is used for DMW and to repair A182 welds which are not stress-relieved after the repair

→ 3 cases out of 300 (cladding, a DMW in A182/A82)

[Efsing2005] P. Efsing, B. Forssgren, R. Kilian "Root cause failure analysis of defected J-groove welds in steam generator drainage nozzles", Proceedings of 12th International Conference on Environmental Degradation of Materials in Nuclear Power Systems – Water Reactors", TMS 2005.

Materials : Alloy 82

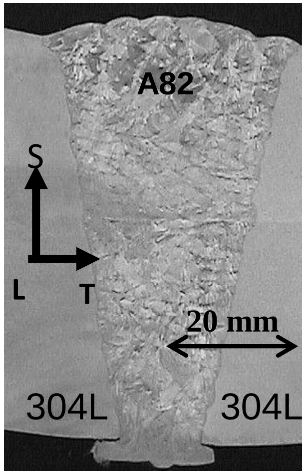
✓ Chemical composition (wt %)

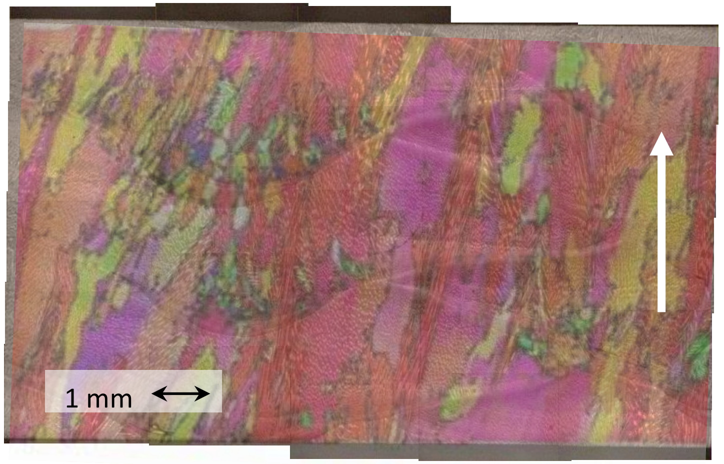
	C	Si	Mn	P	S	Cu	Mo	Ni	Cr	Co	Nb	Ti	Fe
French spec.	<0.1	<0.5	2.5/3.5	<0.03	<0.015	<0.5	-	>67	18/22	<0.1	2/3	<0.75	<3
Weld A	0.014	0.17	2.88	0.002	0.017	<0.01	0.05	72.9	18.15	0.01	2.83	<0.01	2.3
Weld B	0.025	0.07	2.57	0.004	<0.001	<0.01	-	71.7	19.12	0.04	2.41	0.1	3.07

✓ Welding Process

Wire	Welding process	Metallurgical state	weld name
A	FCAW	As-welded	Weld A/AW
B	GTAW	As-welded	Weld B/AW
		Heat-treated (stress-relieved) 7 hr at 600°C	Weld B/HT

✓ Multi-pass V-groove weld

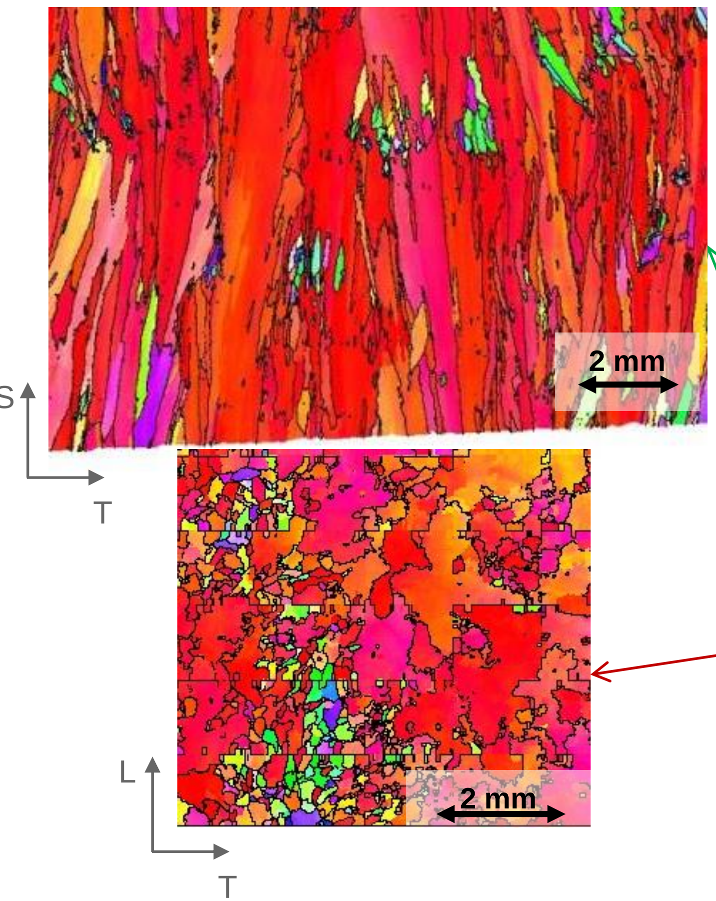


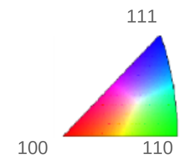


Dendrite growth direction

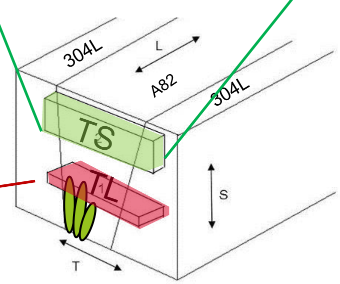
Microstructure

Weld A as-welded

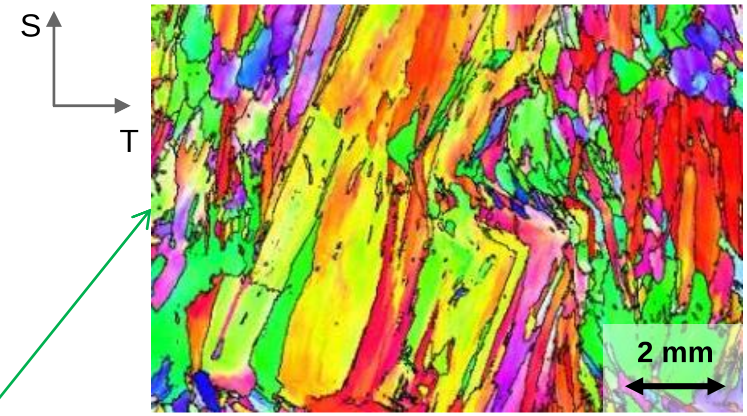


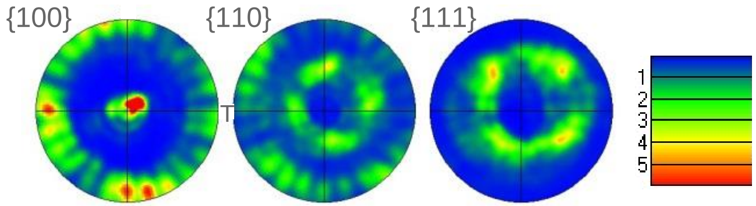


IPF following S axis



Weld B as welded



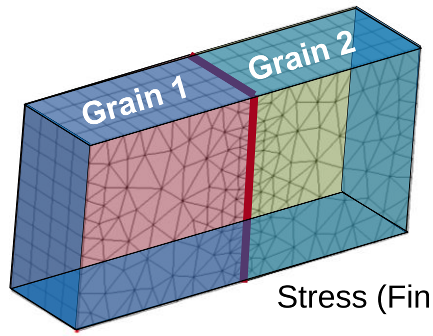


- Heterogeneous grain size and elongated grains along the S direction
- Morphology and texture depends on the weld (on the welding process)
- Representative elementary volume close to 1 cm^3

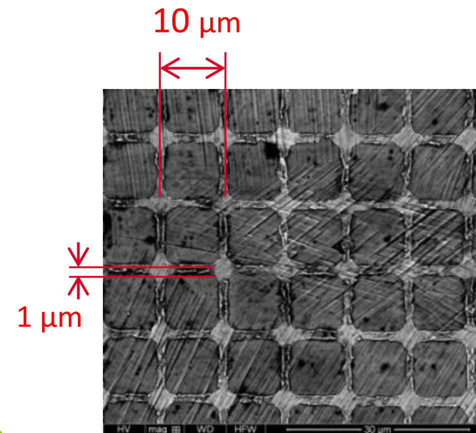
Approach

U-bend specimen tested in hydrogenated steam at 400°C (200 bars)

Microstructural analyses



Stress (Finite elements)



Strain fields
DIC using gold grids

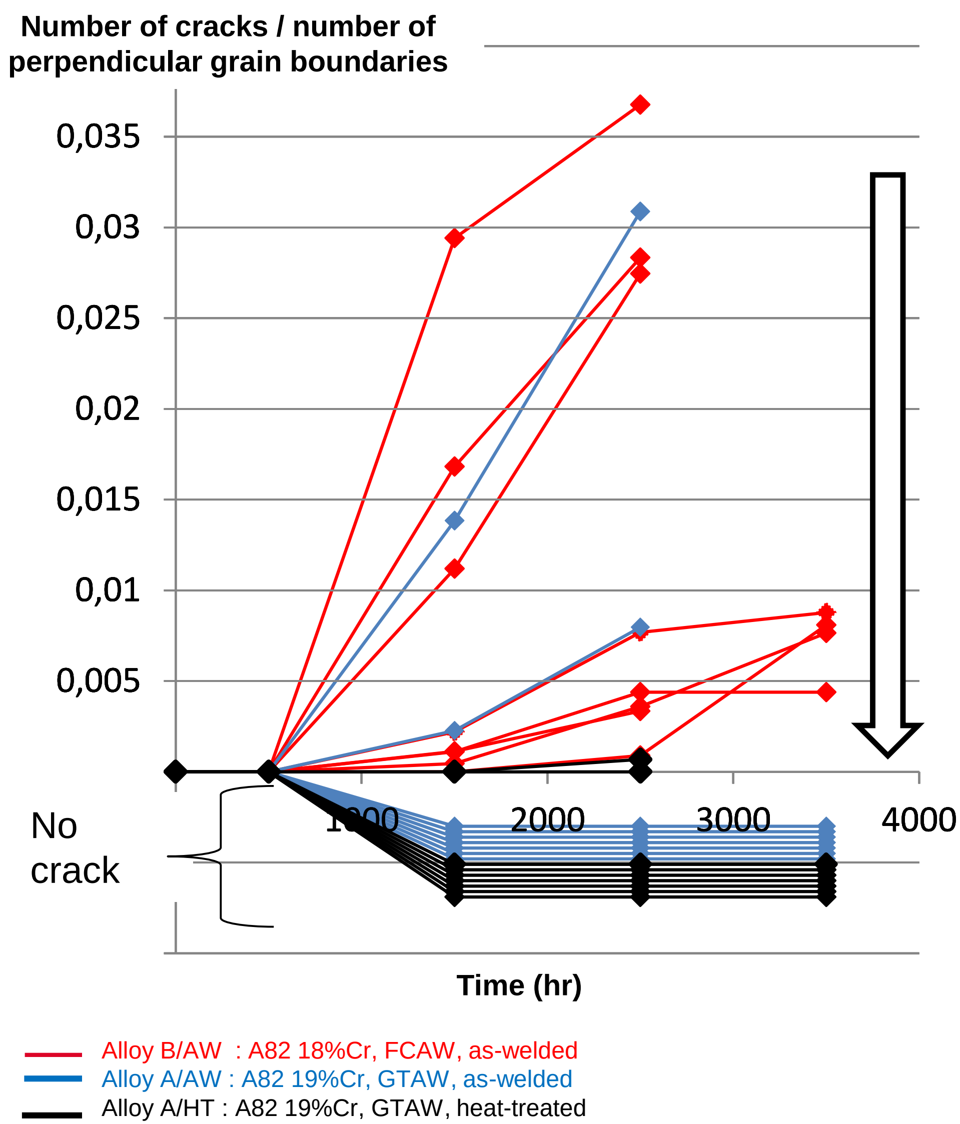
Initiation sites

Local mechanical behavior

To identify which **microstructural parameters associated with local mechanical behavior** enable SCC initiation

Macroscopic behavior → Local behavior

Initiation tests : macroscopic behavior



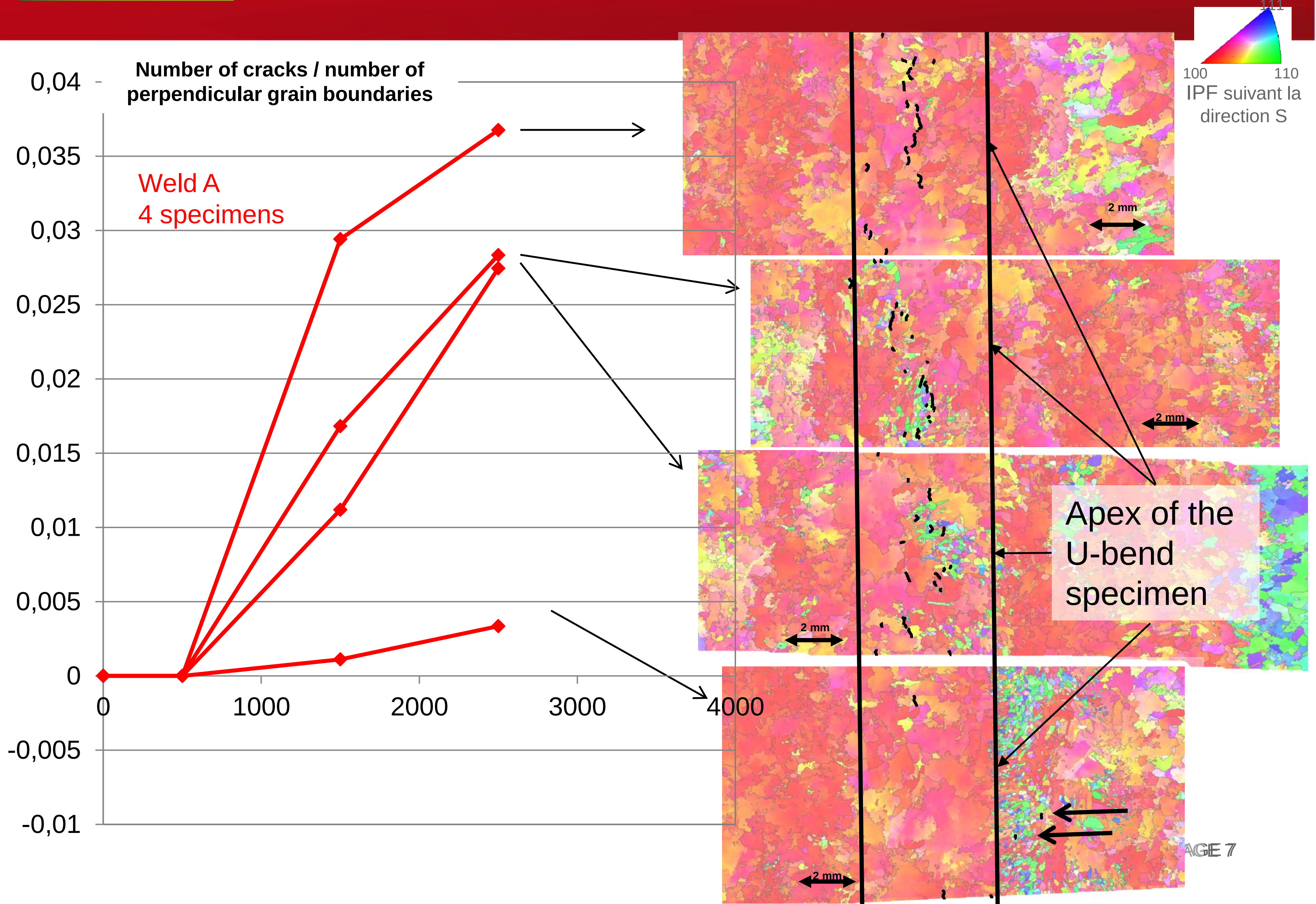
- **Weld B/AW is less susceptible** to SCC than **weld A/AW**

- Weld B/HT is less susceptible than weld B/AW

- "weld to weld" variability
- beneficial effect of the heat treatment assumed to be due to the formation of intergranular chromium carbides [Sennour2013]
- but some scattering for the same weld + specimen size versus REV
- a local approach can be used.

[Sennour2013] M. Sennour et al. JNM, 2013

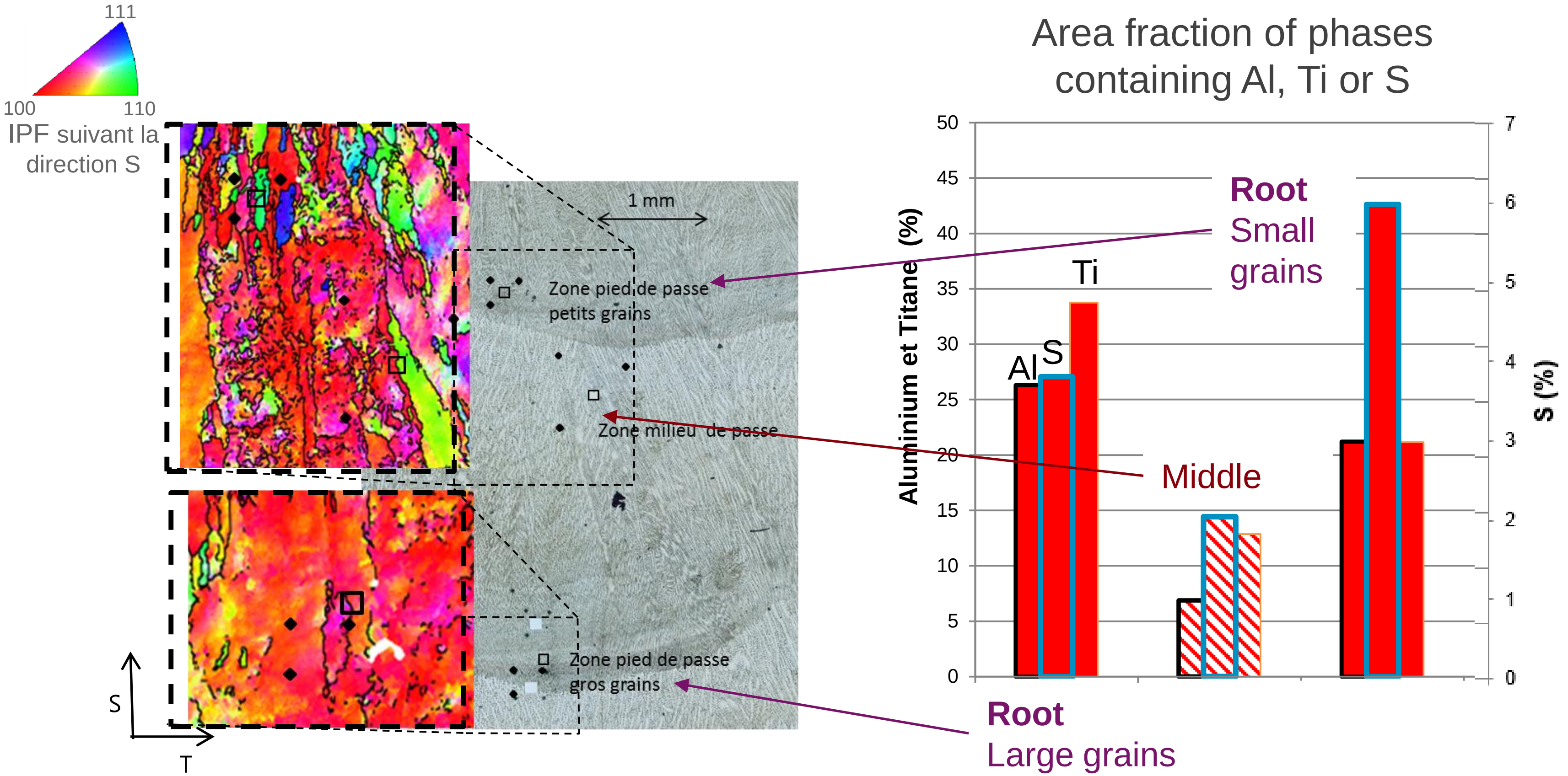
Initiation tests : scattering ?



Chemical heterogeneities in the weld passes

SIMS analysis at different locations in weld passes (weld A):

at the root of the weld pass (with small grains or large grains) and in the middle of the pass



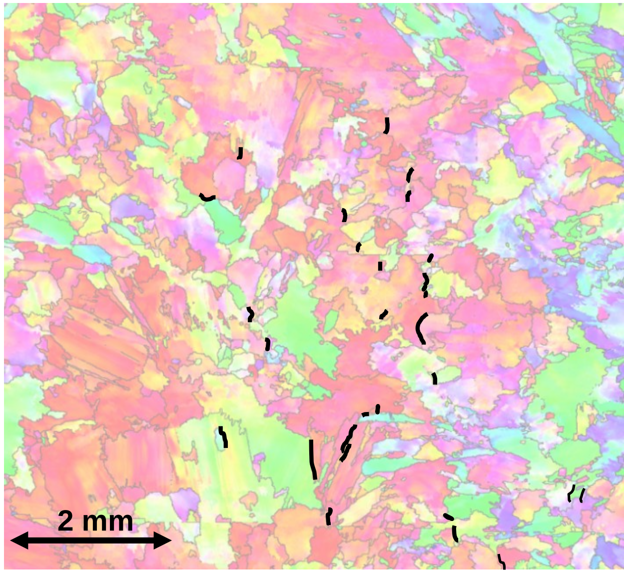
More impurities at the roots of the weld passes (small grains or large grains).

SCC initiation and microstructure ?

Depending of the welding process, the chemical composition or the thermal treatment

- more impurities can be found in some places in the welds (roots of the welds passes for instance)
- chromium carbides can precipitate in the grain boundaries
  - modify the grain boundary cohesion energy

Weld A – as-welded



But for the same chemistry and / or precipitation, not all the grain boundaries crack.

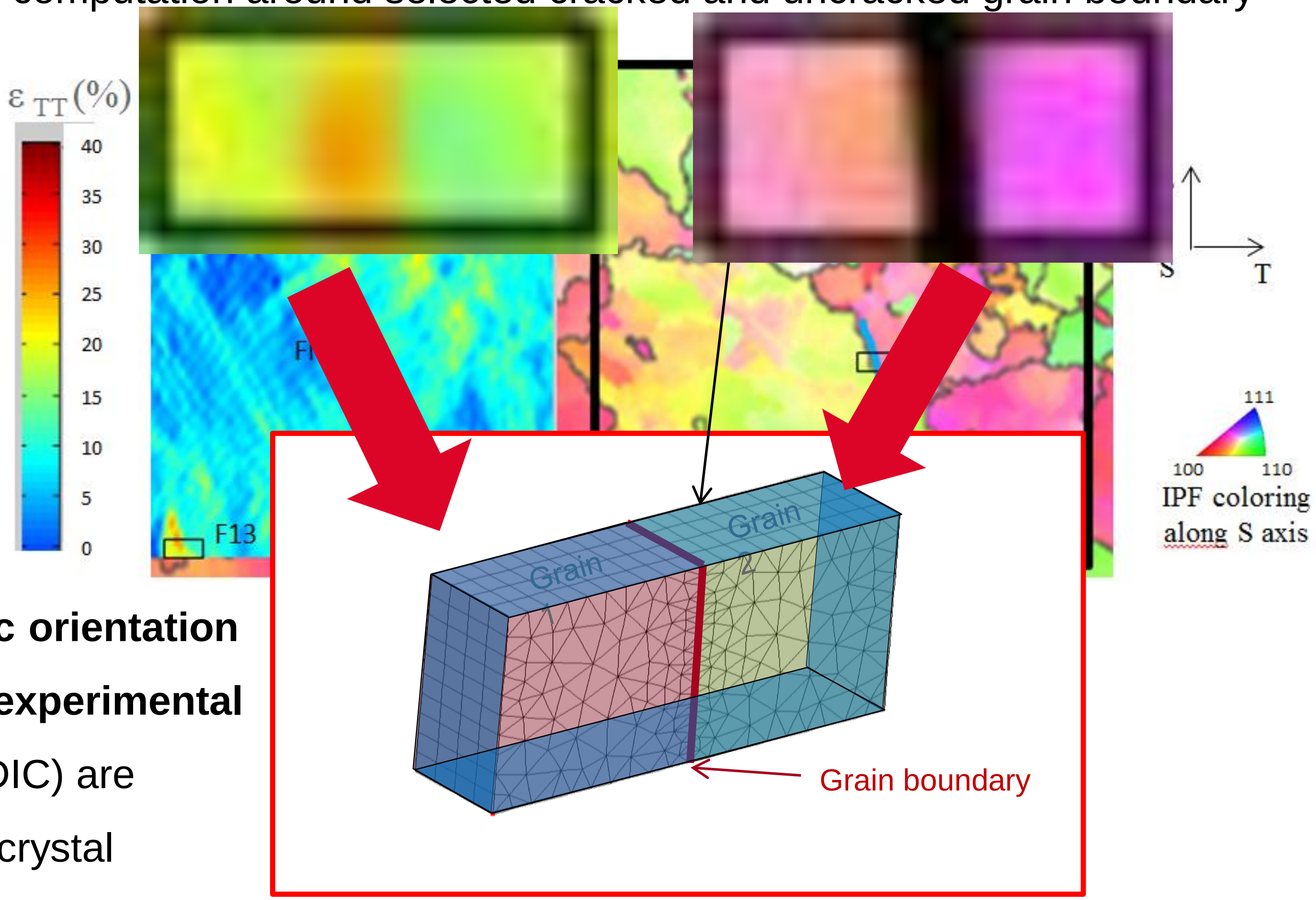
What about the mechanical fields ?

- Strain is not a sufficient parameter to model the SCC initiation behavior [Chaumun et al., 2015] [Chaumun, 2016]
  - **Stress close to the grain boundary (finite elements analysis) ?**

SCC initiation and stress ?

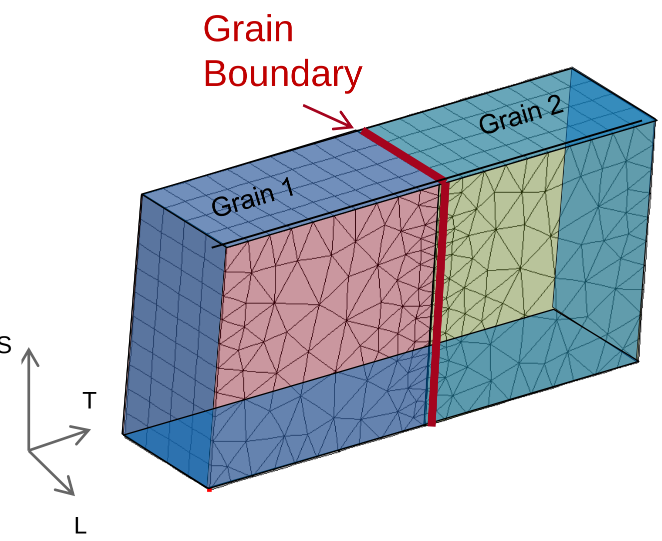
Finite elements computations

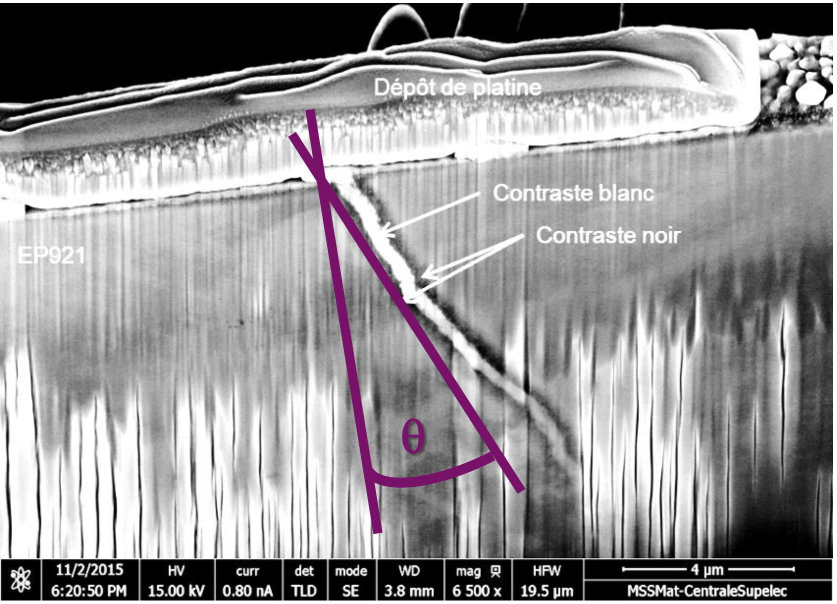
→ Finite elements computation around selected cracked and uncracked grain boundary



- **Crystallographic orientation** (EBSD) and the **experimental displacement** (DIC) are applied to the bi-crystal system.

SCC initiation and stress ?





Parameters in the calculations :

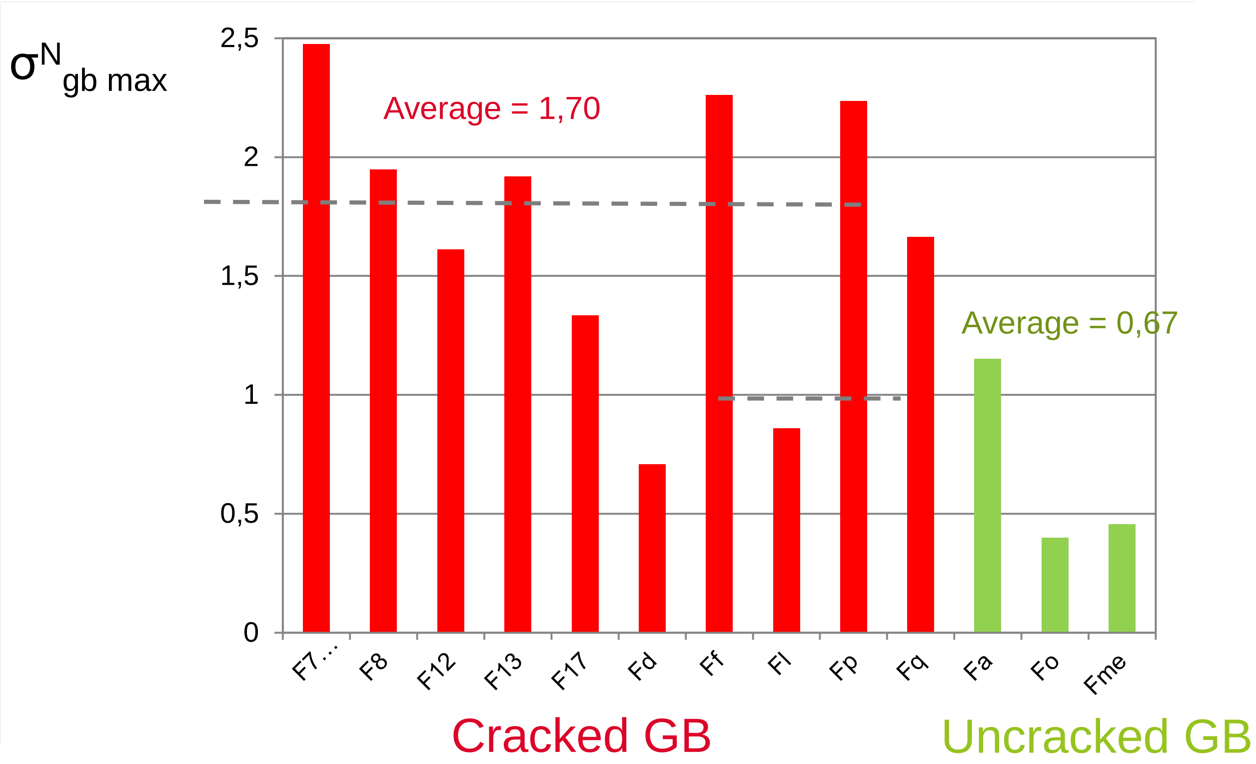
- Cracked and uncracked GB are selected.
- GB are considered as cracked or uncracked depending on FIB characterizations (on each calculated grain).
- Displacement field.
- Crystallographic orientation.
- Angle θ.

Results :

- $\boldsymbol{\sigma}^{N}_{gb}$ = Maximum normal stress $\boldsymbol{\sigma}_{gb}$ normalized by the average normal stress of all computations

SCC initiation and stress ?

→ The average of the normalized maximum normal stress is higher for the cracked GB than for the uncracked ones.



Conclusions

Macroscopic behavior → Local behavior

Alloy 82 is **susceptible to SCC** initiation in hydrogenated steam at 400°C.

Its susceptibility depends on the welding process, chemical composition and thermal treatment

- ➢ the heat treatment can induce intergranular chromium carbides formation that are beneficial. The formation of chromium carbides also depends on the chemical composition (available C and Cr).

The susceptibility depends on the location in the weld passes

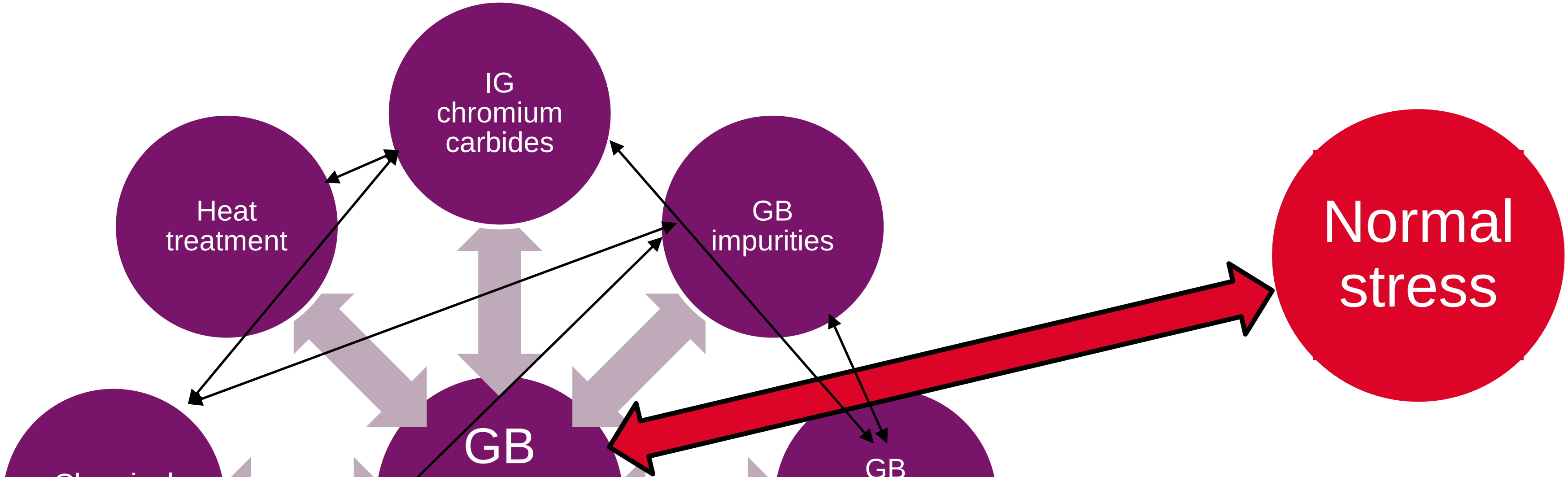
- ➢ the roots of the weld passes can contain more impurities (correlation with the weld process and with the chemical composition).

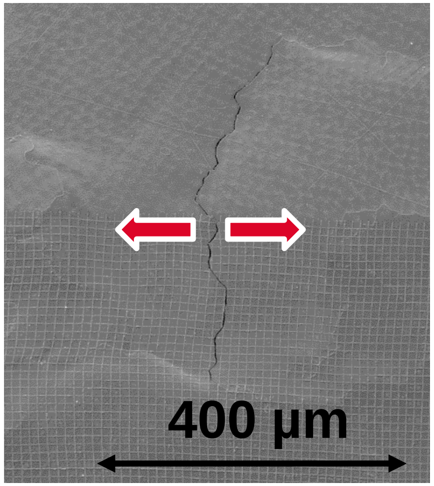
The susceptibility depends on the GB binding energy which depends on the GB chemistry, on the strain discrepancy [Wehbi2014], on the precipitation, …

→ Not only one local parameter can explain the susceptibility of grain boundaries → BUT a coupling of parameters

Tend to a **initiation criterion** = **mechanical behavior** (maximal normal stress and deformation discrepancy) + **chemical parameter** (intergranular oxide, grain boundary cohesion energy)

Conclusions





References

M. Sennour, E. Chaumun, J. Crépin, C. Duhamel, F. Gaslain, C. Guerre, I. de Curières, TEM investigation on the effect of chromium content and of stress relief treatment on precipitation in Alloy 82, Journal of Nuclear Materials, Volume 442, Issues 1–3, November 2013, Pages 262–269

C. Guerre et al., ICG-EAC meeting 2014 and 2015

E. Chaumun, J. Crépin, C. Duhamel, C. Guerre, E. Héripré, M. Sennour, I. de Curières, SCC crack initiation in nickel based alloy welds in hydrogenated steam at 400°C, 17th International Conference on Environmental Degradation of Materials in Nuclear Power Systems – Water Reactors, August 9-12, 2015, Ottawa, Ontario, Canada

E. Deneuvillers – Chaumun, PhD thesis, Mines Paristech, 2016

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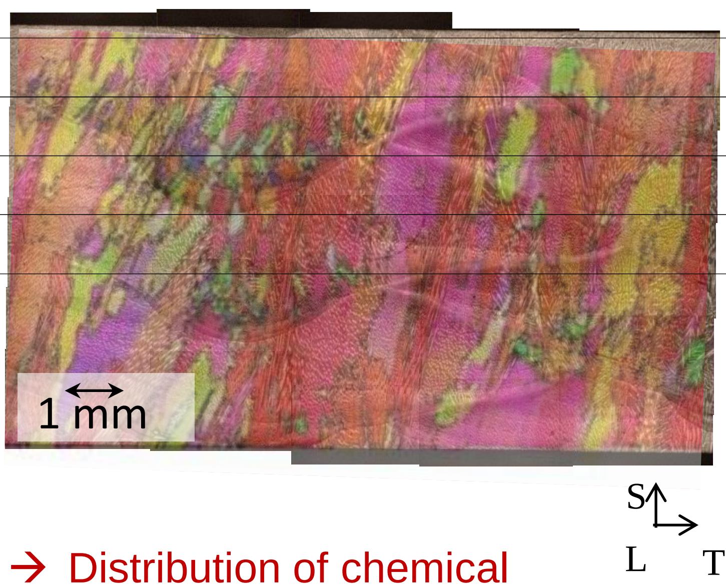
WELDING PROCESS USING FOR GTAW AND FCAW

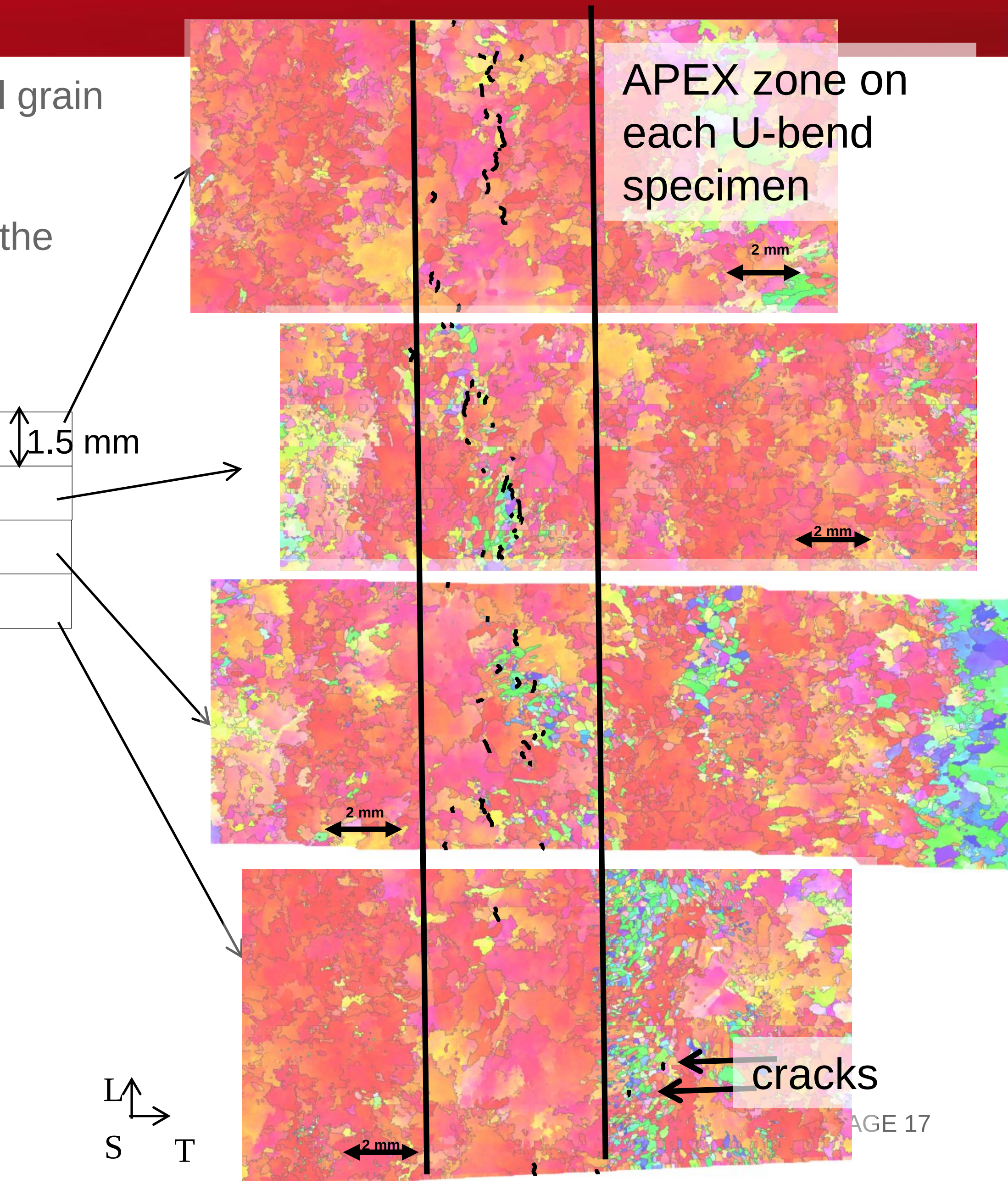
Conditions	GTAW	FCAW
Wire diameter	1 – 1,2 mm	1,2 mm
Current	180A, 13-14V	200-210A, 28-29V
Welding speed	10cm/mn	30cm/mn
Current polarity	DC negative	DC positive
Heating between welding passes	120°C max	120°C max
Passes number	90	90

CHEMICAL HETEROGENEITIES IN WELD PASSES ?

→ Most of the cracks are located in small grain zones

→ Majority of small grains are located at the bottom of weld passes





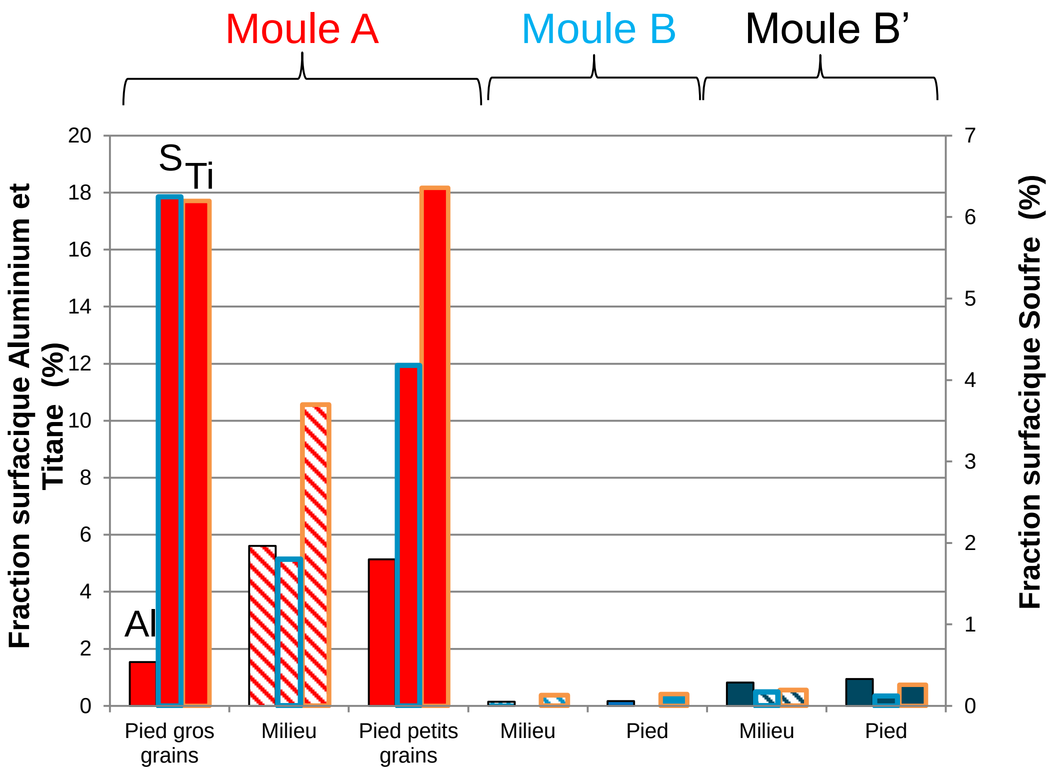
→ Distribution of chemical elements inside weld passes ?

→ SIMS analyses performed in the middle and bottom of weld passes

II) Corrélation sites d'amorçage de fissures / microstructure

Hétérogénéité chimique au sein des passes des moules A/A' et B/B'

- Analyses chimiques intragranulaires par Microsonde de Castaing (cartographies 100 µm x 100 µm)



→ Plus de précipitation d'impuretés dans le Moule **A** **que dans les moules B et B'**

→ Les **moules B et B'** : **peu de différence** entre pieds et milieux de passes

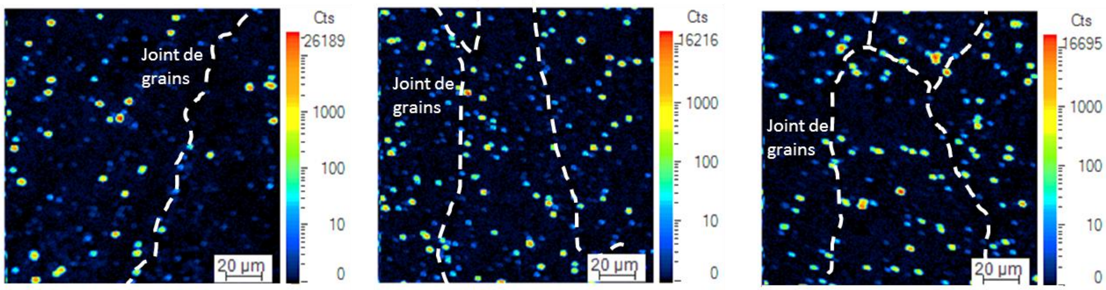
➡ Observation de plus de précipitation intragranulaire en pieds de passes
→ l'hypothèse d'une présence importante d'impuretés intergranulaires

II) Corrélation sites d'amorçage de fissures / microstructure

Analyses chimiques au niveau des joints de grains

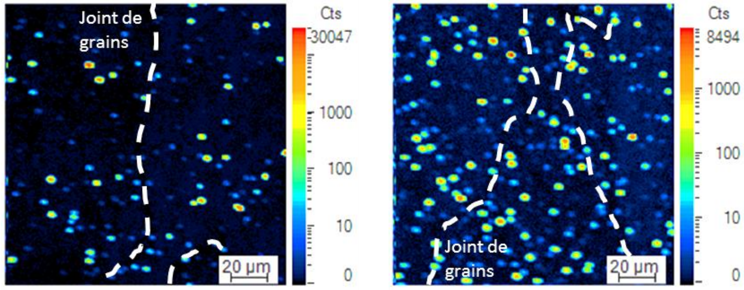
→ Analyses par SIMS en augmentant le rapport signal/bruit (cas du soufre)

Moule A



Zone milieu de passe · Zone pied de passe 1 · Zone pied de passe 2

Moule A'



Zone milieu de passe · Zone pied de passe

➡ Pas de mise en évidence de ségrégation de soufre aux joints de grains par SIMS (dans nos conditions d'analyse)

➡ Mais plus de soufre en pieds de passe

→ Joints de grains (MET) :

Moule A	- NbC (≈ quelques dizaines de nm)
Moule A'	- NbC (≈ quelques dizaines de nm)
Moule B	- NbC (≈ quelques dizaines de nm) - NbC (≈ plusieurs µm)
Moule B'	**-$Cr_{23}C_6$** - NbC

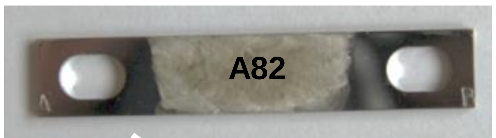
→ Moule B précipitation intergranulaire plus dense que le Moule A

→ Moule A' : pas de formation de carbures de chrome après traitement thermique ≠ Moule B'

SCC INITIATION TESTS DIRECT AND COMPLEX LOADING

Sample dimension and grain size dimension = Representative Volume Element

- ✓ Initiation tests
  - → In an autoclave
  - → Interrupted at 500 hours, 1500 hours, 2500 hours and 3500 hours



Samples dimensions :
50mm x 9mm

dies

U-bend specimen

Direct loading	0 % to +12 %
Complex loading	Step 1 : 0 % to -2 % Step 2 : -2% to +12%

SCC INITIATION TESTS

✓ Initiation tests

→ U – bends specimen
→ Interrupted at 500 hours, 1500 hours, 2500 hours and 3500 hours

Samples dimensions :
50mm x 9mm

U-bend specimen

→ Tests in **hydrogenated steam**

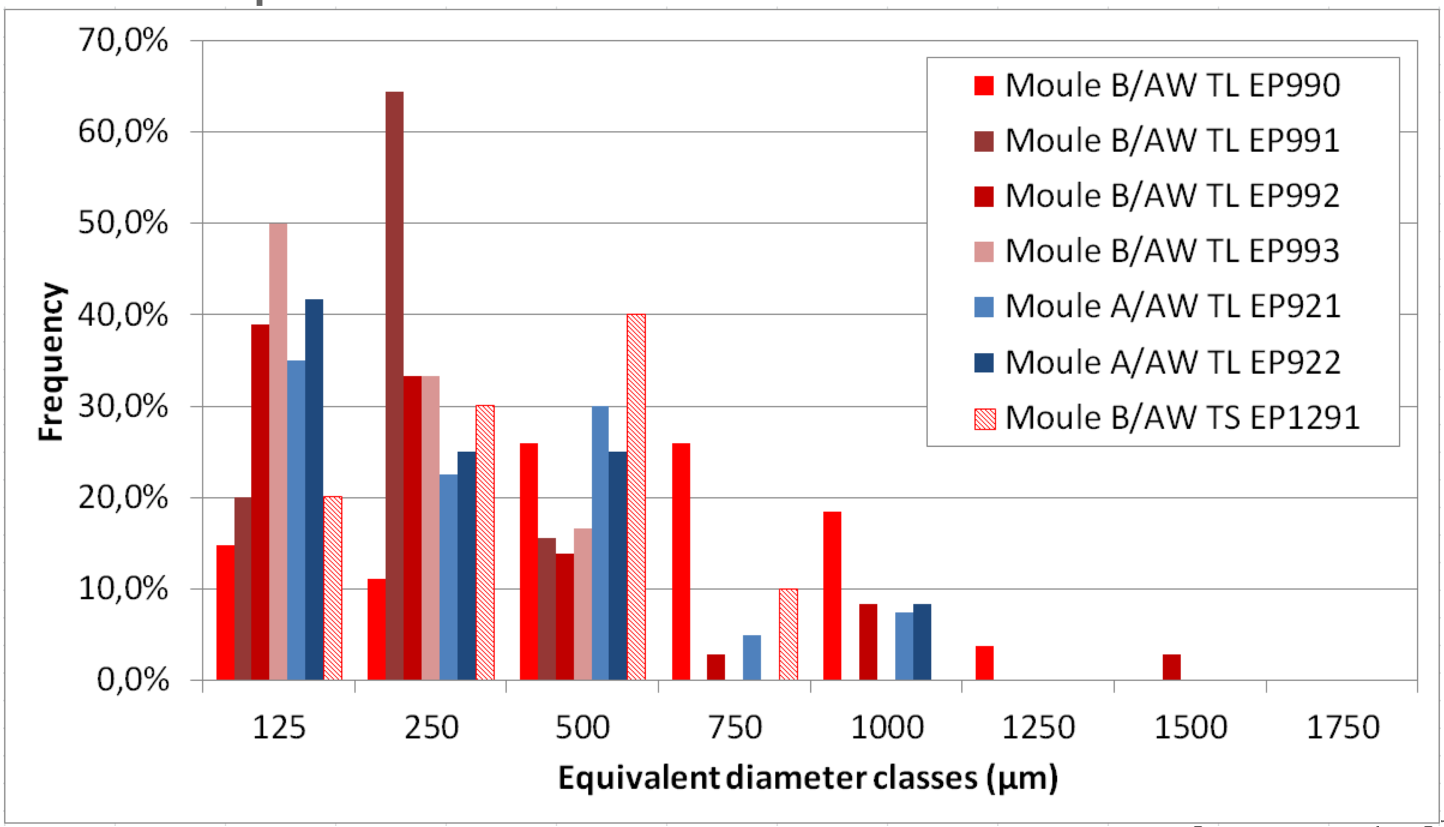
	Conditions
Temperature	400°C
Total pressure	188 bar
Hydrogen partial pressure	0.7 bar

FINITE ELEMENT COMPUTATIONS : STRESS FIELDS ALONG GRAIN BOUNDARY

→ **Cracks are intergranular** (100% of cases), **perpendicular** to the loading direction (95%) and localized on **HAGB** (>15° of misorientation)

→ Majority of **cracked boundaries localized in small grains zones** (58% of concerned grains for A/AW TL and 90% for B/AW TL have an equivalent diameter <500µm

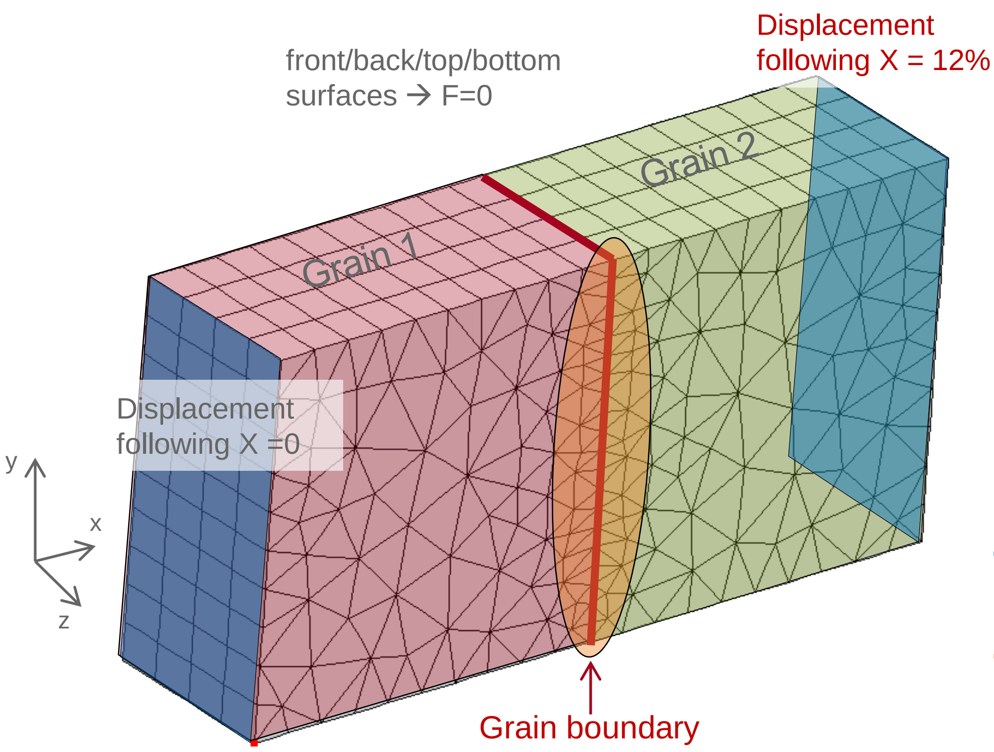
→ Majority of cases highlight : at least **one of the two grains of the couple has a equivalent diameter < 500 µm**



FINITE ELEMENTS COMPUTATIONS : STRESS FIELDS ALONG GRAIN BOUNDARY

✓ Macroscopic boundary conditions

→ Simple finite elements simulation (3D) : 2 grains



→ Crystalline orientations from EBSD analyses

→ Crystalline elastoviscoplatic law with a non-linear isotropic hardening and a linear kinematic hardening (as [Méric-Cailletaud])

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

$\dot{\gamma}$: shearing rate, σ : critical resolved shear stress, X : kinematic hardening, R : isotrope hardening et K,n Norton law parameters

→ Boundary conditions

→ Quadratic mesh, thiner along grain boundary

[Méric-Cailletaud]L. Méric, P. Poubanne, and G. Cailletaud, Journal of engineering materials and technology transactions of the ASME,1991

FINITE ELEMENTS COMPUTATIONS

✓ Experimental boundary conditions (ExBC)

→ Finite elements computation around cracked and uncracked grain boundaries

→ Crystallographic orientation (EBSD)

→ Boundary conditions applied to the outline of the bi-crystal system (experimental displacement)

→ Crystalline elastoviscoplatic law with a non-linear isotropic hardening and a linear kinematic hardening (as [Méric-Cailletaud])

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

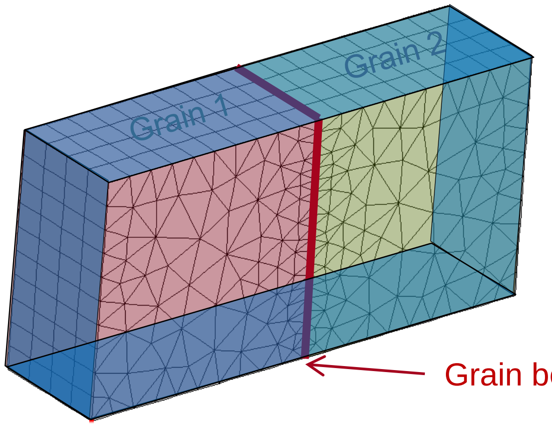
$\dot{\gamma}$: shearing rate, σ : critical resolved shear stress, X : kinematic hardening, R : isotrope hardening K,n Norton law parameters

Parameter (units)	Value
E (Mpa)	164955
υ	0,33
n	6,505
K	31,6
Ro (MPa)	100
Q (MPa)	6000
h	5,8
C	66000

Ro, Q, h: non-linear isotropic hardening

C: linear kinematic hardening

front/back/top/bottom surfaces → F=0



Displacement on the outline of the by-crystal system = local deformation

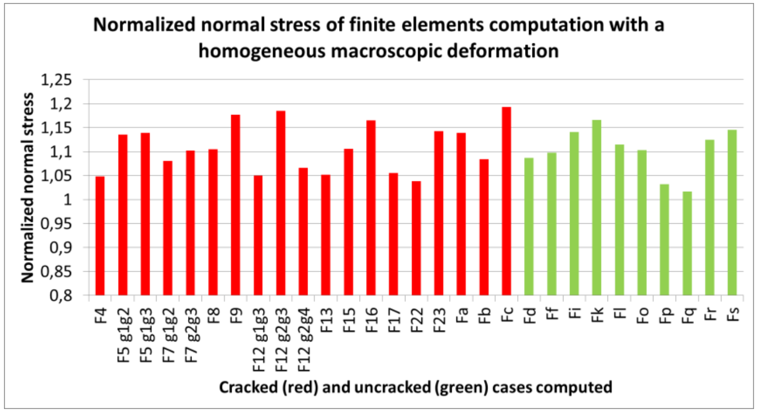
→ Quadratic mesh, thinner along grain boundary

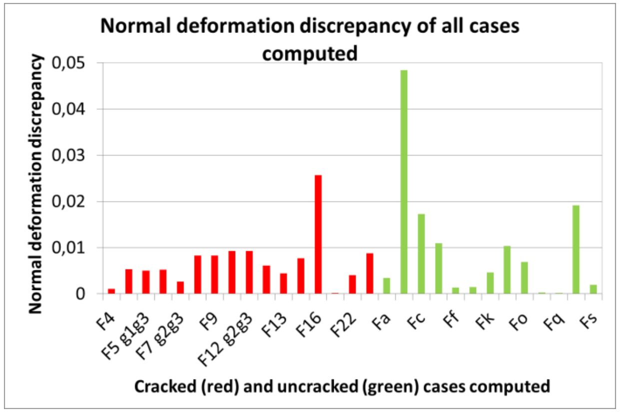
[Méric-Cailletaud]L. Méric, P. Poubanne, and G. Cailletaud, Journal of engineering materials and technology transactions of the ASME,1991

FINITE ELEMENTS COMPUTATIONS : STRESS FIELDS ALONG GRAIN BOUNDARY

✓ Macroscopic boundary conditions

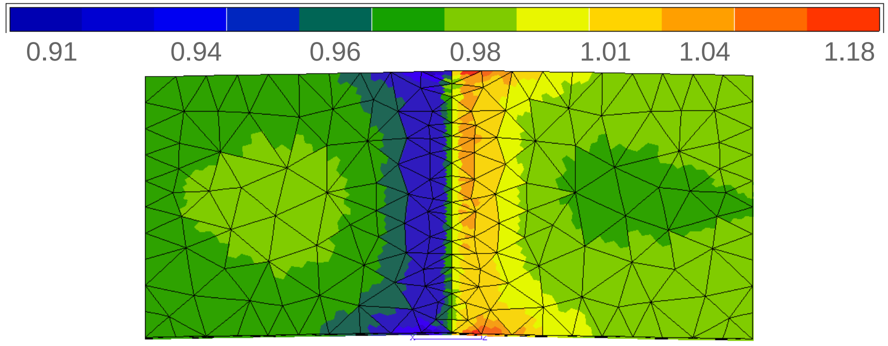
→ Finite element computations made on:
- cracked grain boundaries
- uncracked grain boundaries

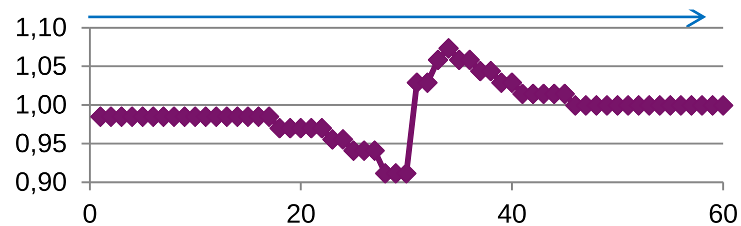




Cracked boundaries
Uncracked boundaries

Normal stress normalized with the average stress





→ Normalized normal stress profile measured at Gauss point from left grain to right grain

→ Stress localized at grain boundary in both cases (cracked and uncraked)
→ No differences between cracked and uncracked boundaries
→ Apply to the bi-crystal system the local and experimental deformation