

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

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DE LA RECHERCHE À L'INDUSTRIE

<u>Ceaden</u>





L' L' POLYTECHNIQU SCC CRACK INITIATION IN NICKEL BASED ALLOY WELDS IN HYDROGENATED STEAM AT 400°C.

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Faire avancer la sûreté nucléaire

Ceaden Context

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



- 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

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

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





[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.

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Ceaden Materials : Alloy 82

✓ Chemical composition (wt %)

	С	Si	Mn	Р	S	Cu	Мо	Ni	Cr	Со	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	Metallurgical state	weld name	
Α	FCAW	As-welded	Weld A/AW	
		As-welded	Weld B/AW	
P	CTA\A/	Heat-treated		
D	GIAW	(stress-relieved)	Weld B/HT	
		7 hr at 600°C		

✓ Multi-pass V-groove weld





Dendrite growth direction

Ceaden Microstructure

Weld A as-welded

Weld B as welded



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Approach



Ceaden Initiation tests : macroscopic behavior

Number of cracks / number of perpendicular grain boundaries



- 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.

Ceade∩ Initiation tests : scattering ?



Ceaden 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).

Ceaden 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

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) ?

Weld A - as-welded



Ceaden SCC initiation and stress ?

Finite elements computations



→ Finite elements computation around selected cracked and uncracked grain boundary



Ceaden 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 :

σ^N_{gb} = Maximum normal stress σ_{gb} <u>normalized</u>
 by the average normal stress of all computations

Ceaden SCC initiation and stress ?

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



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)

DE LA RECHERCHE À L'INDUSTRIE

Ceaden 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

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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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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		

Ceaden chemical heterogeneities in weld passes ?



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



S↑

1 mm

→ 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)



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

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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'



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

\rightarrow 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'	- Cr₂₃C₆ - 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'

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SCC INITIATION TESTS DIRECT AND COMPLEX LOADING

✓ Initiation tests

Sample dimension and grain size dimension = Representative Volume Element

- \rightarrow In an autoclave
- \rightarrow Interrupted at 500 hours, 1500 hours, 2500 hours and 3500 hours



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



Ceaden scc initiation tests

✓ Initiation tests

- \rightarrow U bends specimen
- \rightarrow Interrupted at 500 hours, 1500 hours, 2500 hours and 3500 hours



Samples dimensions : 50mm x 9mm

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



FINITE ELEMENTS COMPUTATIONS : STRESS FIELDS ALONG GRAIN BOUNDARY

- Macroscopic boundary conditions
- \rightarrow 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



Ceaden FINITE ELEMENTS COMPUTATIONS

Experimental boundary conditions (ExBC)



 \rightarrow Finite elements computation around cracked and uncracked grain boundaries

164955

0.33

6.505

31,6

100

6000

5.8

66000

- → 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

→ Quadratic mesh, thinner along grain boundary

front/back/top/bottom surfaces \rightarrow F=0



non-linear isotropic hardening

linear kinematic hardening

Environmental Degradation 2015 | August 2015 | PAGE 24

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

E (Mpa)

Ro (MPa)

Q (MPa)

υ

n

κ

h

С

FINITE ELEMENTS COMPUTATIONS : STRESS FIELDS ALONG GRAIN BOUNDARY

Macroscopic boundary conditions

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





Normal stress normalized with the average stress



- → 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

Cracked boundaries Uncracked boundaries