Stress corrosion cracking in primary components in Pressurised Water Reactors

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IAEA Training Workshop TR 47184, Madrid, September 2014
STRESS CORROSION CRACKING IN THE PRIMARY LOOP OF PRESSURISED WATER REACTORS

✓ INTRODUCTION

✓ PWSCC OF NICKEL BASE ALLOYS

✓ SCC of AUSTENITIC STEELS

✓ IASCC OF AUSTENITIC ALLOYS
Stress corrosion cracking is one of the mode of a more general phenomena named Environmentally Assisted Cracking (EAC) that includes:

- Stress Corrosion Cracking (SCC)
- Strain induced cracking
- Corrosion fatigue
- Hydrogen embrittlement

Cracking of a metal under the combined effects of a static stress and a specific chemical environment
Stress corrosion cracking is a phenomena slow time dependent that produces services failure in structural materials.

SCC can initiate at pre-existing surface features (grooves, weld defects,..) highly cold worked surface layers, pitting, localized corrosion (IGA, emerging slip planes on the surface), ....
Key parameters for Stress Corrosion Cracking

- Required tensile stress are small, lower than the macroscopic yield strength
- SCC cracks growth without evident macroscopic evidence of mechanical deformation in ductile materials

Sensitized SS in LWR Ni-base alloys in PWR
Typical in chloride environments
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Primary water stress corrosion cracking (PWSCC) is the name given to the intergranular cracking of nickel base alloys in PWR primary water conditions.

Alloy 600, weld metal 82 and 182, X-750 in primary loop
Extensive PWSCC reported from 1972 in plants with steam generator tubes of Alloy 600. Later, thick components such as CRDM were also affected.

Weld metals 82 and 182 are also susceptible to PWSCC.

Numerous R&D projects on this topic (parametric, mitigation, ...)

Empirical models are available for engineering purposes.

No mechanism understanding is available.

New materials for replacement and new plants (Alloy 690 and weld metals 52 and 152)
SCC susceptibility of austenitic alloys

PWSCC susceptibility increases with Ni content and decreases with Cr content.

The role of the main alloys elements on the SCC susceptibility of austenitic alloys depends on the environment.
First cracks in Bugey 3 in 1991

- ID axial cracking in front to the weld CRDM/RPV
- Crack propagation in the base metal and in the weld metal
- Circumferential cracks initiated in the external diameter

Davies Besse cracking in 2002

- Axial cracks initiated inside the Alloy 600 tubes
- Circumferential cracks at the outside diameter
- Boric acid corrosion of the RPV head (LAS)
The weld metals of Alloy 600, weld metals 82 and 182, are also susceptible to PWSCC.

**V.C. Summer in 2000**
- Cracks in one repaired and grinded weld.
- Through wall axial crack with circumferential branching in the weld metal.
- Cracks do not propagate in the low alloy steel.

**PWSCC of Alloy 600 and weld metals 82 and 182**
What is known about PWSCC of Alloy 600 and their weld metals

- Bad microstructure, high mechanical properties and low chromium content increase susceptibility.
  - Heats with a high density of carbide in grain boundaries are more resistant.

- Time to failure decreases as applied stresses increase
  - Stresses about 0.8 times the elastic limit are required

- Susceptibility increases as local cold work increases

- Susceptibility decreases as uniform cold work increases, if total stress at surface remain constant

- Crack growth rate increases as stress intensity factor increases

- Crack growth rate is maximum for hydrogen level near the Ni/NiO phase transition
What is known about PWSCC of Alloy 600 and their weld metals

Initiation process

\[ \frac{1}{t_i} = A \sigma^n e^{-Q/RT} \]

- \( t_i \): initiation time
- \( \sigma \): effective stress acting on the component
- \( n \): es 4-5
- \( Q_i \): Activation energy for initiation, 44 kcal/mol
- \( R \): constant
- \( A \): constant depending on material and environment

Propagation process

\[ \dot{a} = \exp \left[ -\frac{Q_s}{R} \left( \frac{1}{T} - \frac{1}{T_{ref}} \right) \right] \alpha (K - K_{th})^\beta \]

- \( \dot{a} \): crack growth rate at \( T \) (m/sec)
- \( Q_s \): Activation energy for propagation, 31 kcal/mol
- \( T \): absolute operating temperature
- \( T_{ref} \): absolute reference temperature (325°C)
- \( \alpha \): crack growth amplitude
- \( K \): crack tip stress intensity factor, MPa√m
- \( K_{th} \): crack tip stress intensity factor threshold, 9 MPa√m
- \( \beta = 1.16 \)

\[ \begin{align*}
E_a \text{ (initiation)} & \to 185 \text{ kJ/mol (44 kcal/mol)} \\
E_a \text{ (propagation)} & \to 130 \text{ kJ/mol (31 kcal/mol)}
\end{align*} \]
Crack growth rate curves for Alloy 600 and weld metal Alloy 182 in primary water

Alloy 600, MRP 55 curve

Alloy 182, MRP 115 curve
Hydrogen control

Typical H$_2$ concentrations are between 25-35ccH$_2$/kgH$_2$O
EPRI proposes to operate at higher H$_2$ concentrations to minimize CGR
Japanese strategy propose to operate with lower H$_2$ concentrations

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Zn additions to primary water increase the PWSCC initiation time.

- Zn addition causes a release of Fe, Co, and Ni from the oxide layers.
- Zn is incorporated into the oxide layers. Oxide layers with Zn are more protective.

Zn concentrations to mitigate initiation cracking are between 20-40 ppb as ZnAc.
The influence of Zn additions on the crack propagation of Alloy 600 is not clear.
Mitigation of PWSCC of Alloy 600 and their weld metals

Mechanical Mitigation of PWSCC

- Mechanical Stress Improvement Process (MSPI)
- Under Water Laser Peening (ULP)
- Water Jet Peening (WJP)
- Air Laser Peening (ALP)

Key issue: introducing compression stresses in susceptible areas to PWSSC

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Public meeting NRC-Industry, 2014
Alloy 690 TT and its weld metals present a high resistant to PWSCC in most laboratories experiments. These alloys have accumulated more than 20 years of operation without any cracking indications.

The available CGR data for thick-walled Alloy 690 in the normal metallurgical condition are of no engineering significance. This conclusion seems to be valid even for materials with a certain grade of cold work.

But, high values of CGR have been obtained for inhomogeneous deformed Alloy 690 base material
Alloy 690 as an alternative to Alloy 600

In plant components, welding introduces modifications in the base metal

\[ \downarrow \]

Microstructure, hardness, residual stresses and retained plastic deformation
Large observed dispersion may be a consequence of differences in the tests and materials conditions.

- Temperature
- Hydrogen content in water
- Ki factor
- Heat treatment
- Degree of Cold Work
- Procedure of cold work application
- Crack orientation
- Weld, base materials

Under some conditions used in lab experiments (inhomogeneous cold worked material), the crack growth rates of Alloy 690 TT in primary water conditions (PWR) is unexpectedly high.
**PWSCC Alloy 690 initiation time**

**Alloy 690TT for CRDM Nozzle**

Comparison of PWSCC Initiation Data of Alloy 690TT CRDM Nozzle Penetration Material with those of Alloy MA600 SG tube

- **Environment:** Simulated Primary Water (B: 500 ppm, Li: 2 ppm)
- **Temperature:** 360°C

**Graphical Data:**
- Stress (MPa) vs. Test Time (hours)
- Max. 95000 hours
- No rupture

**Microscopic Image:**
- Ti inclusions may act as cracking precursor

**Test Methods:**
- Constant load tests

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Overall performance of austenitic stainless steels in primary water conditions is adequate but SCC does occur.

- Most ID failures at locations with off-nominal chemistry and/or stagnant conditions.
- Few events of ID SCC in nominal primary water:
  - pressurizer heaters,
  - drain line connections,
  - safe-ends.
  - others

Cold work is a prime factor in SS SCC in both off-chemistry and normal environment.
Cold work increases the SCC susceptibility of austenitic stainless steels and nickel base alloys by modifying the three key parameters:

- Stress
- Strain rate
- Strength

Cold work results from the interactions of dislocations that eventually immobilize them, producing a higher strength material.

More strain produces more dislocations sources and more immobilization, leading to higher strength.

Stahele, 2008
In the fabrication of LWRs, cold work can occur due to:
Bending, cutting, machining, boring, grinding, honing, ...

Surface hardness Rc 22-26
2-6 mils from the surface

Grazing X-ray diffraction on austenitic stainless steel
Cold worked austenitic stainless steels show higher cracks growth rates and lower crack initiation times.

Required conditions for SCC in normal primary water hardness level > 240 HV 0,1 for initiation and > 310 HV0,1 for propagation.
Influence of oxygen and impurities in off-chemistry water conditions

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Couvant, 2010
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IASCC: Influence of irradiation on SCC key parameters

Grain boundary segregation

Hardening

Susceptible Material

Tensile Stress

Environment

Δ ionic transport

$E_{\text{cor}}, \text{pH}$
It is accepted that IASCC can appear when the material has accumulated a level of fluence higher than the “fluence threshold”: $5 \times 10^{20} \text{ ncm}^{-2}, E > 1 \text{ MeV}$
IASCC in PWR: Baffle former bolts

**Baffles**
- Core Barrel
- SA304L (18%Cr-10%Ni)

**Bolts**
- CW316E or CW316L (17%Cr-11%Ni-2.5%Mo)

900 - 1000 bolts depending on the design
Radiation induced segregation (RIS)

Cr depletion
Ni, Si and P enrichment

Cr depletion is a function of dose

Cr depletion seems to be saturated for dose ~ 5 dpa

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Radiation produces an increase in yield strength and a decrease in the fracture toughness.

Radiation creep relaxation occur in the same range of fluence that radiation hardening and RIS. The effect net is generally beneficial.
• Point defect clusters at low fluence ("Black dots")
• Dislocation loops appear at several dpa
• At very high fluence, He bubbles, voids and precipitates are possible

• Small clusters and loops dominate at < 300°C
• Larger loops and cavities at higher temperatures
• Interaction of the loops with the dislocation network under stress gives rise to hardening
A dependence between yield strength of materials and IASCC is observed, similar to the one in non irradiated materials, in both types of reactors. Cr depletion due to RIS seems to play a role in BWR but not in PWR.
Susceptibility to cracking increases with dose
Critical stress level for initiation decreases with dose
At high doses (>70 dpa), IASCC initiates at stresses 40-60% of the irradiated YS

Chopra, 2011
IASCC crack growth rate in PWR

(a) Experimental CGR (m/s)

- Irradiated Stainless Steels
- PWR Environment
- Normalized to 320°C

(b) Empirical/theoretical model

- da/dt Adjusted to 310°C (m/s)

Chopra, 2011

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Future challenges

Influence of high Li and dynamic loading on the IASCC susceptibility.

Crack growth rate data in high irradiated materials.

New materials resistant to IASCC

Predictive model for long operation time

Stainless steels, nickel base alloys

Mechanistic models for PWSCC

New crack growth rate data for Alloy 690 in representative conditions

Initiation time data for Alloy 690 to define an improvement factor respect to Alloy 600