Crack Growth in the Through-Thickness Direction of Hydридed Thin-Wall Zircaloy Sheet

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Acknowledgments

- Harold Scott and Ralph Meyer, NRC
- Sébastien Carassou, Olivier Rabouille and Christophe Poussard, CEA Saclay
- Jean Desquines, IRSN Cadarache
Outline

• Background and motivation
• Experimental and analytical procedures
  – Materials and hydriding
  – Hydride microstructure characterization
  – Fracture toughness testing
• Experimental results
  – Load-displacement behavior
  – Fracture behavior
• Fracture toughness interpretation
  – Fracture mechanics interpretation
  – J-R curve behavior
  – Influence of hydrogen and temperature
• Conclusions
Background – RIA Failures

• Crack initiation and growth due to PCMI
  – Reactivity Insertion Accident

• Crack initiation in reduced ductility zones
  – Hydride rims and blisters

• Failure by through-thickness crack growth

➢ To predict failure on the basis of crack growth, it is necessary to know the fracture toughness of the material in the through-thickness direction.
Motivation

• Many fracture toughness studies on zirconium alloys
  **BUT...**
• Studies often performed on thick (5mm-6mm) plate or tube configurations
  – Actual cladding tubes have a very thin wall (~600 μm)
• Axial crack growth
  – Very few through-thickness crack growth studies
• Little data at 300° C and above
  – In-service temperatures are ~300° C-350° C

➢ No studies of through-thickness crack growth in thin-wall components
Goals

- The primary purpose of this study is to investigate the fracture toughness behavior for **through-thickness** crack growth using **thin sheet** specimens of cold work and stress relieved Zircaloy-4 as a model material
  - As a function of hydride microstructure
  - As a function of temperature (up to 375°C)

- Identification the micro-mechanisms that control crack growth resistance as a function of hydride microstructure and temperature

- Achieved by performing a fracture toughness test on 4-point bend specimen containing a linear hydride blister to initiate a crack
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Materials – Texture

- CWSR Zircaloy-4 thin sheet provided by ATI - Wah-Chang
  - Texture and mechanical properties similar to previously studied materials
- Basal poles oriented at ~30° from the sheet normal in the transverse direction

<table>
<thead>
<tr>
<th>Direction</th>
<th>Normal Radial</th>
<th>Transverse Circumferential</th>
<th>Rolling Axial</th>
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</thead>
<tbody>
<tr>
<td>Present study CWSR sheet</td>
<td>0.59</td>
<td>0.29</td>
<td>0.12</td>
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<tr>
<td>Direct pole figure method</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inverse pole figure method</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Previous studies</td>
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<td>0.31</td>
<td>0.16</td>
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<tr>
<td>CWSR sheet¹</td>
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<td>0.31</td>
<td>0.05</td>
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<tr>
<td>CWSR tube²</td>
<td>0.58</td>
<td>0.32</td>
<td>0.10</td>
</tr>
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</table>

Materials – Flow Behavior

- Material properties in the **transverse direction** after stress relief heat treatment for **2 hours at 520°C**

<table>
<thead>
<tr>
<th></th>
<th>$\sigma_{0.2%}$ (MPa)</th>
<th>n</th>
<th>$\epsilon_r$ (%)</th>
<th>P</th>
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<tbody>
<tr>
<td><strong>25°C</strong></td>
<td></td>
<td></td>
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<tr>
<td>Previous studies at PSU with CWSR sheet$^1$</td>
<td>573</td>
<td>0.01</td>
<td>19</td>
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<td>CWSR Sheet (this study)</td>
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<td>NA</td>
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<tr>
<td><strong>300°C</strong></td>
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<td></td>
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<tr>
<td>Previous studies at PSU with CWSR sheet$^1$</td>
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<td>0.03</td>
<td>16</td>
<td>1.6</td>
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<tr>
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<tr>
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<td><strong>375°C</strong></td>
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<td>CWSR Sheet (this study)</td>
<td>290</td>
<td>0.027</td>
<td>22</td>
<td>1.6</td>
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</table>

Hydrogen Charging Procedure

- Oxide removal
- Gold sputtering
- Gold removal by scribing
- Nickel deposition/window
- Gas-charging in $\text{H}_2/\text{Ar}$ at 400° C and 9psi pressure
- Annealing

![Image of hydrogen charging process]

Anneal at 400° C & slow cool
Characterization of Hydride Microstructure

- Hydride microstructure varied through the thickness of the specimens
- Important to characterize the local hydride microstructure to understand its influence on fracture toughness
- Image analysis software was used to obtain a quantitative description of hydride microstructure
  - Image-J was used to predict the hydrogen content
  - Hydromorph was used to calculate the radial hydride content
Hydrogen Content Estimation

- Area fraction measurements may be converted to hydrogen contents
- Calculated hydrogen contents were calibrated by hot vacuum extraction
- Etching results in an over-estimation of the hydrogen content by a factor of ~15
Hydride Orientation

Hydromorph

- Image analysis software developed by the CEA and IRSN
  - Skeletization and indexing of hydrides
  - For each hydride particle, Hydromorph provides length and orientation
- We define:
  - $0^\circ < \theta < 40^\circ$ for in-plane hydrides (IHC)
  - $40^\circ < \theta < 65^\circ$ for mixed hydrides (MHC)
  - $65^\circ < \theta < 90^\circ$ for out-of-plane hydrides (OHC)

$$MHC = \frac{\sum L_j^{mixed}}{L_{total}}$$

- Radial Hydride Fraction

$$RHF = 0.5 \times MHC + OHC$$
Fracture Toughness Testing

- 4-point bending
- Fatigue pre-cracking
- Electrical potential drop
- Load-displacement and crack growth curves
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Load-Displacement and Crack Growth Behavior

- At 25°C load decrease occurs
  - Stable crack growth: gradual
  - Unstable crack growth: abrupt drop

- At 300°C and 375°C
  - Large plastic deformation plateau near maximum load
  - Crack tip blunting

![Load-Displacement and Crack Growth Behavior Graph](image)
Fracture Behavior

- Hydride assisted cracking at 25°C

- Large crack opening with little crack extension at 300°C and 375°C
  - Crack tip blunting
  - Failure expected to occur by shear instability as observed previously
  - No obvious role of hydrides

100 μm
SEM Fractography

- Confirms metallographic observations
- At 25°C: hydride-induced primary voids linked by ductile failure
- At 300°C: ductile failure, ridges observed (‘ductile’ hydrides?)
- At 375°C: ductile failure, very large ductile dimples
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Fracture Mechanics

- Elastic-plastic fracture mechanics
  \[ J_{i_{\text{tot}}}^i = J_{i_{\text{el}}}^i + J_{i_{\text{pl}}}^i = \frac{K_i^2 \cdot (1 - \nu^2)}{E} + J_{i_{\text{pl}}}^i \]
  \[ K_j' = \sqrt{\frac{J_{i_{\text{tot}}}^i E}{(1 - \nu^2)}} \]

- J-R curves generated
- Specimen-size dependent fracture toughness
  - thin-wall cladding behavior
- Finite element modeling used to ‘fine-tune’ the elastic-plastic fracture mechanics analyses
  - Cast3M and Franc3D

B: specimen width
\( b = W - a \), with \( W \) the specimen thickness
\( a \): crack length
\( A_{\text{pl}} \): plastic energy spent by the applied load
Typical J-R Curves

- Crack growth observed at 25°C
- Only blunting observed at 300°C and 375°C
Influence of Hydrogen and Temperature

- Strong decrease in fracture toughness above 20% radial hydrides and 200wt.ppm hydrogen at 25° C
- Little or no influence of radial hydride fraction and hydrogen content at 300° C and 375° C within the range tested
Conclusions

Fracture toughness of unirradiated thin-sheet CWSR Zircaloy-4 was investigated for conditions of through-thickness crack growth, as a function of the hydride microstructure and at temperatures of 25°C, 300°C and 375°C.

- New experimental procedure
  - New hydriding procedure
  - Through-thickness crack growth in thin sheet
- Local characterization of hydride microstructure
  - Hydrogen content and hydride orientation
  - Microstructure gradient
- Elastic-plastic fracture mechanics
  - Fine tuned with finite element modeling
  - J-R curves produced
Conclusions

- At 25°C, the fracture toughness and fracture process influenced by the hydride microstructure
  - Decrease from ~45MPa√m to ~10MPa√m with increasing hydrogen content and radial hydride fraction
  - Crack growth process controlled by formation of hydride-induced primary voids
- At 300°C and 375°C, the material is very resistant to the initiation of stable crack growth
  - Crack extension due to large amounts of crack-tip blunting
  - Failure would occur by shear instability
  - No cracking of hydrides and no effect of hydrides on fracture process
  - Toughness independent of hydride microstructure
  - $K_J > 50$ MPa√m at 300°C and $K_J > 52$ MPa√m at 375°C
Thank you for your attention
Backup Slides
Grain Structure

16th Int. Symp. on Zr in the Nuc. Ind. - Chengdu, China, May 2010
Modeling of Uneven Cracks with Franc3D

- Elastic fracture mechanics modeling of uneven cracks
- The fracture toughness is lowest where the cracks were the shallowest
- Shallowest portions of the crack front advance first at 25°C
- Crack front advances uniformly at 300°C and 375°C

![Graphs showing crack length vs. x for 25°C and 300°C or 375°C (similar behavior)]
Fracture Toughness Calculations with Cast3M

- 2D quadratic mesh
- Spider-web crack tip
- J-integral is dependent on the $\eta_{pl}$ parameter

$$J_{tot} = J_{el} + J_{pl} = \frac{K^2(1-v^2)}{E} + \frac{\eta_{pl}A_{pl}}{b \cdot B_n}$$

- Results different from thick specimen geometries

$$\eta_{pl} = \frac{\partial J_{pl}}{\partial \left( \frac{A_{pl}}{b \cdot B} \right)}$$