

Mechanical behavior at high temperature of highly oxygen- or hydrogen-enriched α and (prior-) β phases of zirconium alloys

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MECHANICAL BEHAVIOR AT HIGH TEMPERATURE OF HIGHLY OXYGEN- OR HYDROGEN-ENRICHED α AND (PRIOR-) β PHASES OF ZIRCONIUM ALLOYS

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Cea

INTRODUCTION











Mechanical behavior and integrity of the oxidized cladding during and after LOCA-like thermal-mechanical transients? Mechanical behavior at high temperature of the α_{Zr}(O) phase containing more than 2 wt.% of oxygen?

⁽²⁾ Mechanical behavior at high and low temperature of the (prior-) β_{Zr} phase containing up to 3000 wt.ppm of hydrogen?





Materials and experimental procedures

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Microstructure of model materials

- Average oxygen contents: 2, 3.2, 4.3 and 5.8 wt.%
- Zirconia completely reduced and oxygen concentration rather homogeneous within the samples (with the exception of the one with 5.8 wt.% of O in average)
- Oxygen-enriched model materials mainly composed of α_{Zr}(O) grains, enriched in O and depleted in Nb and Fe (0 to 15% of residual untransformed β_{Zr} phase)

Coarse lamellae or large grains ($\geq 100 \ \mu m$)



Zircaloy-4, oxidized 600s in steam at 1100°C





Microstructure of model materials

Texture (EBSD, neutron diffraction) comparable to that measured for the α_{Zr}(O) phase formed during oxidation in steam at HT



Model α_{Zr}(O) phase reasonably representative of the α_{Zr}(O) phase observed in claddings oxidized at HT





Viscoplastic flow

Two creep regimes, depending on stress level





Creep resistance increases with increasing the oxygen content (*e.g.* strain rate of $\alpha_{Zr}(2 \text{ wt.}\% \text{ O})$ 100-1000 times slower than that of α_{Zr} phase without O addition)



Viscoplastic flow

Modeling:



Effect of the residual β_{Zr} phase relatively small





Viscoplastic flow

Modeling:



Strain regime	A (K.MPa ⁻ⁿ .s ⁻¹)	п	Q (kJ.mol⁻¹)	В
Linear	5.75·10 ³	1	180	0.53
Power-law	4.80·10 ³	5	222	2.29

Effect of the residual β_{Zr} phase relatively small











② Mechanical behavior between et low ad high temperature of the (prior-) β_{Zr} phase containing up to 3000 wt.ppm of hydrogen?





Materials and experimental procedures

Prepared from low-tin Zircaloy-4 cladding tubes



Hydrogen content measured for each sample by using an inert gas fusion thermal conductivity technique (+ DSC, µ-ERDA and neutron radiography on a selected number of samples) → Satisfactory of hydrogen the samples

Satisfactory homogeneity of hydrogen content within the samples



Materials and experimental procedures







Materials and experimental procedures

Prepared from low-tin Zircaloy-4 cladding tubes





fast strain rate in order to minimize metallurgical evolutions and oxidation of the material during the test

(faster than the rates at which the cladding can be subjected during a LOCA transient)





Elasticity and plastic isotropy

Young's modulus and plastic isotropy not significantly modified by the presence of high H contents



2D digital image correlation → Young's modulus and plastic strain anisotropy







Fracture





Cross-section reduction

at failure ~98%

Fracture





Plasticity

- When the behavior is macroscopically ductile, the flow stress of the (prior-) β_{Zr}
 phase containing between 1700 and 3200 wt.ppm of H is, compared to the one of the non-hydrided material
 - higher at 500°C and below

Proeutectoid α_{Zr} enriched in O and depleted in H



Prior- β_{Zr} transformed below the eutectoid temperature, depleted in O but containing a very large amount of H at least partially precipitated under the form of strengthening nano-hydrides

Figure: Highly hydrided material

lower at 700°C



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 β_{7r} with all H in

solid solution





Oxygen and hydrogen are known to be the main parameters responsible for embrittlement of zirconium alloys

① Mechanical behavior between 800 and 1100°C of the α_{Zr}(O) phase containing between 2 and 5.8 wt.% of oxygen?

- Creep resistance of the oxygen-enriched α_{Zr}(O) material increases with increasing O content, significantly higher than the creep resistance of the as-received material without additional O
- Two creep regimes observed: power-law regime for stresses higher than 15 MPa and nearly linear regime for lower stresses (further investigation needed to identify the mechanisms that drive the linear creep regime)
- Model α_{Zr}(O) materials ductile between 800 and 1100°C for O contents between 2 and 3.2 wt.%, brittle, even at 1100°C, for O contents higher than 4 wt.%





⁽²⁾ Mechanical behavior between 20 and 700°C of the (prior-) β_{Zr} phase containing between 1700 and 3200 wt.ppm of hydrogen?

- Young's modulus and plastic isotropy not substantially modified by H
- Material embrittled by H contents of 1700-3200 wt.ppm for temperatures below 500°C: macroscopically brittle at 135°C and below for average H content of ~2000 wt.ppm and at 350-400°C for ~3000 wt.ppm of H (further work to be done to determine the underlying mechanisms responsible for the effects of high H contents)
- Effect of H on macroscopic ductility diminishes when temperature increases and becomes negligible beyond 500°C
- When the behavior is macroscopically ductile, the flow stress of the material containing between 1700 and 3200 wt.ppm of H is higher than the one of the nonhydrided material at 500°C and below, and lower at 700°C

Thank you for your attention

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