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The Effects of Hydride Rim on the Ductility of Zr-based Nuclear Fuel Cladding

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1. Introduction

During operation in nuclear reactor the cladding tube forms a hydride rim that resides above a substrate that is relatively free of hydrides. A prediction of the ductility of such cladding tubes must take into account: the density of the hydrides as a layer/rim and the rim thickness, the ability of the hydrides to deform, their circumferential orientation within the layer, and the presence of a relatively unhydrided substrate.

Recent experiments based on unirradiated cladding tubes containing hydrides in the form of a rim indicate a significant loss of ductility with (a) increasing hydrogen content [*1*] and/or (b) increasing hydride rim thicknesses [*2*]. These results suggest that a ductile-to-brittle transition occurs with increasing hydride rim thickness. Since the hydride rim initiates a crack early in the deformation process, fracture mechanics has been recently used to predict failure on the basis of crack propagation. While this type of analysis can be applied to brittle cladding with thick hydride rims, failure of cladding with small- thickness hydride rims exhibits significant ductility; importantly, this cladding does not appear to obey fracture mechanics, as the fracture stress approaches the tensile strength of the cladding.

2. Failure Sequence Due To Hydride Rim

The failure sequence can be discussed as follows.

2.1. Initiation of microcracks

Recent observations indicate that microcracks (= 0.5 mm surface length) initiate at very small strains (essentially zero strain [*2*]). Also, the density of these microcracks decreases with increasing hydride layer thickness. Thus, thick hydride layers (> 150 μm) initiate a single deep crack which extends across the entire specimen (~ 6 mm), resulting in near-brittle behavior.

2.2. Micro-crack linkage

When the hydride rim is thin (< 90 μm thick), the growth and linkage of microcracks into a long (surface) crack results in cladding ductility. This second stage appears to depend on both the density of cracks and their depth. A high density of very shallow (~ 20 μm thick) microcracks will link rather quickly with strain, forming a long (> 2 to 3 mm) but shallow surface crack. In contrast, a lower density of more widely spaced and *non-coplanar* surface cracks of *intermediate* depth (i.e., ~ 75 μm) will link with difficulty. In this case, cladding ductility also occurs during this strain-induced linking of moderately deep cracks into a tortuous, long surface crack.

2.3. Failure of the substrate

Failure of the cladding substrate below the hydride rim depends on rim depth, with strain to failure increasing as hydride-rim depth decreases. The through-thickness growth of shallow cracks in cladding with a thin hydride layer is difficult, and significant crack opening displacement (and material ductility) occurs before substrate fracture occurs due to damage accumulation at room temperature or shear instability at 300°C at stresses significantly greater than the yield stress. Cladding with a hydride-rim of medium depth (~ 75 μm) has a tendency to link microcracks that are *not co-planar* and to form a tortuous fracture path through the substrate; ductility results as the failure stress exceeds the yield stress.

Finally, cladding with thick hydride layers initiates a long (> 3 mm) surface crack that propagates easily as a "deep", planar crack through the substrate, near-brittle behavior of the cladding results, likely obeying a criterion based on hydride rim thickness/crack "depth".

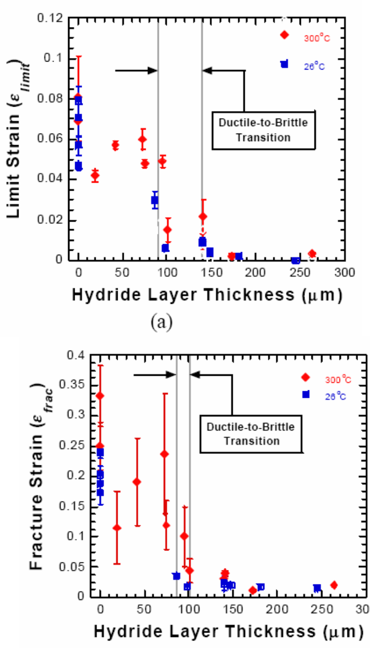
3. Effects of Hydride Rim

The cladding fracture strain, ε_{frac}, is the measure of the local strain required for cladding fracture. Fig. 1 shows the dependence of both the limit strain (Fig. 1a) and the fracture strain (Fig. 1b) on thickness of the hydride layers in Zircaloy-4 cladding tubes deformed in near plane-strain tension to failure at room temperature and 300°C. The most important characteristic in Fig.1 is the obvious dependence of cladding ductility on hydride-layer thickness. At both room temperature and 300°C, the ε_{limit} values (Fig. 1a) indicate a gradual ductile-to-brittle transition with increasing hydride layer thickness. Especifically, cladding with hydride rims of thicknesses ≥140 μm show little or no plastic deformation to failure. In view of the fact that the experimental accuracy of measurements of local strain is ±0.01 (±1%), these cladding tubes are essentially brittle. At the 100 μm hydride thickness level, there may be a small level of plastic deformation to the cladding prior to failure. However, cladding samples with hydride-rim thicknesses <90 μm are distinctly ductile, with hoop limit strains of roughly 0.04 or greater.

It is not straightforward to relate these failure strain values to cladding fracture under an RIA transient. If localization of strain is induced by friction resulting from pellet-cladding interactions, ε_{frac} could be an important parameter in characterizing cladding failure susceptibility. On the other hand, if fuel pellet-cladding friction is minimal, ε_{limit} could be the more appropriate failure criterion.

It is tempting to consider results such as those in Fig. 1 on the basis of hydrogen content. Typically, these studies have associated a significant loss of ductility with increasing hydrogen content, such that the factor controlling the ductile-to-brittle transition is assumed to be the overall hydrogen level. Available data indicate that cladding specimens with hydrogen content in the 500~800 wtppm range but different hydride layer thicknesses fail at widely varying values of ductility. Thus, for the case of a hydride rim, it can be concluded that the total hydrogen content is not the best measure of cladding ductility, but that the ductile-to-brittle transition is better defined by hydride rim thickness. Such a result contrasts with the case for uniformly distributed hydrides across the entire cladding thickness, in which the factor controlling the ductile-to-brittle transition is the overall hydrogen level.

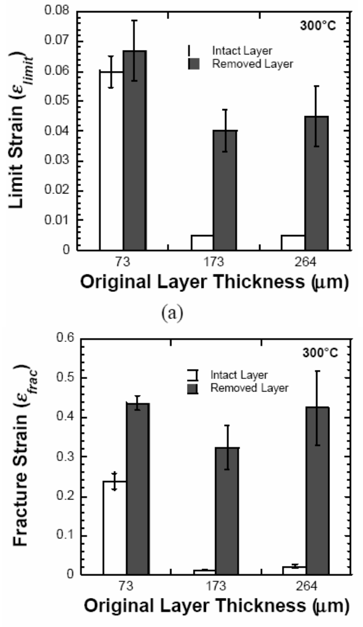
Fig. 2 is based on the behavior of *sibling* specimens with the hydride rim intact and mechanically removed. These results indicate that the previously brittle cladding is ductile once the hydride layer is removed. Removing the hydride rim restores the ε_{limit} and ε_{frac} values to levels close to those determined for unhydrided cladding.



(a)

(b)

Figure 1. (a) Limit strain (ε_{limit}) and (b) fracture strain (ε_{frac}) as a function of temperature and hydride layer thickness (Robert S. Daum, 2002)



(a)

(b)

Figure 2. (a) Limit strain (ε_{limit}) and (b) fracture strain (ε_{frac}) at 300ºC as a function of original hydride layer thickness (Robert S. Daum, 2002)

4. Conclusions

From the review on the effects of hydride rim on the fracture behaviors of Zy-based cladding, the following conclusions were drawn.

First, cladding ductility is very sensitive to hydride rim thickness at both room temperature and 300°C. This sensitivity is manifested in a loss of ductility with increasing hydride rim thicknesses, such that the cladding is ductile when the hydride rim thickness is less than 90 mm, but it is brittle at hydride rim thicknesses of approximately 140 μm and greater.

Second, the failure mechanism of hydrided cladding involves three stages: (1) microcrack initiation with crack depth equal to hydride rim thickness, (2) growth and linkage of microcracks into a long surface crack, and (3) failure of the relatively hydride-free ligament by either crack growth due to damage accumulation (room temperature) or the formation of a shear instability beneath a blunted crack (300°C).

REFERENCES

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[2] R.S. Daum et al., “On the Embrittlement of Zircaloy-4 under RIA-Relevant Conditions,” *13th Inter. Sym. on Zr in the Nucl. Industry* (West Conshohocken, PA: ASTM, 2002).