A Review on the Variables Affecting Failure Strain of Nuclear Fuel Cladding During Reactivity Initiated Accident

Sunki Kim, Jegeon Bang, Chanbock Lee, Daeho Kim, Yongsik Yang

Korea Atomic Energy Research Institute, 150 Deokjin-dong Yuseong-gu, Daejeon 305-353, Korea
kimsk@kaeri.re.kr

1. Introduction

The crucial mechanical property for nuclear fuel cladding survival under reactivity initiated accident (RIA) is the cladding ductility. In this paper, main parameters affecting failure strain of fuel cladding during RIA are discussed, aiming at identifying key parameters for the clad ductility.

2. Variables affecting failure strain during RIA

2.1 Influence of cladding temperature

The influence of clad temperature on failure strain is shown in figure 1, which comprises failure strain data from un-irradiated material with low hydrogen content, determined in tests with low strain rates. More precisely, the average hydrogen content was below 15 ppm, and the strain rate was less than 10^{-3} s^{-1} for the presented data.

It is interesting to note that the spread in data is significant, even for these un-irradiated samples, taken from clad tubes in as-fabricated condition. Moreover, the spread is just as large within individual test series, as it is between different series. From the presented data, it is not possible to discern notable differences between Zircaloy-2 and Zircaloy-4. However, figure 1 indicates superior room-temperature ductility for Zircaloy-2. Finally, it should be noticed that the effect of temperature on the ductility of hydrided cladding is much more complex than for the almost hydride-free cladding shown in figure 1.

2.2 Influence of strain rate

In figure 2, the results of tests performed under high strain rate to the data presented in figure 1 were added. At a strain rate of 1 s^{-1}, the failure strain is below 2%, irrespective of clad temperature. Although the failure strain is higher in the high-temperature tests, the high- and low temperature data follow the same trend with respect to strain rate. Hence, we may conclude that the embrittling effect of increased strain rate is not significantly influenced by temperature, as long as un-irradiated cladding with negligible hydrogen content is concerned. However, this conclusion is not valid for hydrided cladding.

2.3 Influence of irradiation

The influence of irradiation on the clad failure strain is shown in figure 3. All data are taken from tests at low strain rate (<10^{-3} s^{-1}), and the data for irradiated material refer to samples with low hydrogen content. Accordingly, the embrittling effects of elevated strain rate and hydrogen are negligible for the data presented here. The fast neutron fluence for the irradiated material ranged from 6×10^{23} to $1.2\times10^{26}/m^2$(E≥1MeV). At these fluences, the irradiation-induced embrittlement is believed to be saturated.

Clearly, the irradiated material has a typical failure strain of about 2%, which is significantly lower than for un-irradiated material. However, for the highest temperature covered by the data (673 K), the irradiated material shows a significantly higher ductility. This is probably due to thermal annealing of irradiation damage, which at 673 K is believed to be sufficiently fast to take place under testing of the material(Torimaru et al., 1996).

2.4 Influence of hydrogen

The influence of hydrogen on clad ductility is a complex matter, which is much more difficult to characterize than the effects of irradiation damage or strain rate. The embrittling effect of hydrogen is strongly affected by temperature, and there is a ductile-to-brittle transition for the hydrided material at a certain temperature. The ductile-to-brittle transition depends on three parameters: hydrogen concentration, temperature and strain rate. Figures 4 and 5 show the measured failure strain with respect to clad average hydrogen content at room temperature and high(523-673K) temperature, respectively. In the figures, distinction is made between data from low (<10^{-3} s^{-1}) and high (>10^{-1} s^{-1}) strain rate tests.

From figure 4, it is clear that the combination of low temperature and high strain rate is extremely detrimental to clad ductility; the failure strain falls off by roughly two orders of magnitude as the hydrogen content exceeds 500 wppm. At low strain rate, the embrittling effect of hydrogen is somewhat milder, but still, the plastic failure strain is reduced to less than 1% in the hydrided material. The embrittling effect of hydrogen is much less pronounced at elevated temperature.

As shown in figure 5, the failure strain in tests performed at low strain rate and temperatures between 523 and 673 K is only weakly affected by clad hydrogen content. A comparison between figures 4 and 5 clearly shows that there is a ductile-to-brittle transition temperature (DBT) for hydrided cladding, and that the DBT is to be found in the range 300 to 520K.

3. Summary

From the review on variables affecting failure strain of nuclear fuel cladding during reactivity initiated accident, the followings can be summarized.

First, the variables affecting failure strain of nuclear fuel cladding during reactivity initiated accident comprize cladding temperature, strain rate, irradiation and hydrogen content.

Second, the data regarding the variables affecting failure strain is so spread because the effects on the failure strain are very complicated and the database was generated from different test condition.

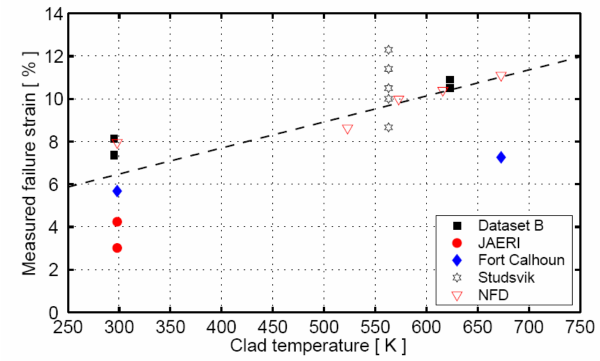

Figure 1. Clad failure strain vs. temperature for un-irradiated claddings with negligible hydrogen content, tested at low strain rate. Filled symbols: Zircaloy-4. Open symbols: Zircaloy-2.

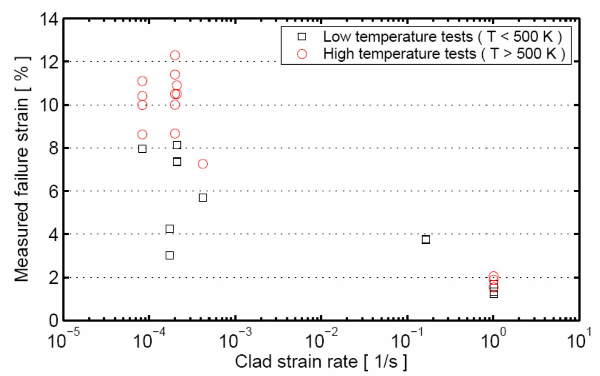

Figure 2. Clad failure strain vs. hoop strain rate for un-irradiated cladding with negligible hydrogen content (<15 ppm).

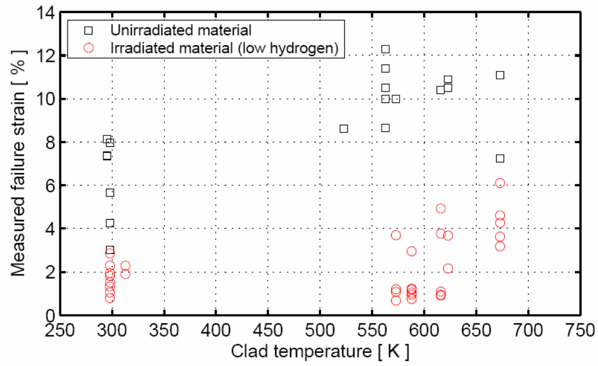

Figure 3. Clad failure strain vs. temperature for un-irradiated and irradiated claddings at low hoop strain rate (<10^{-3} s^{-1}).

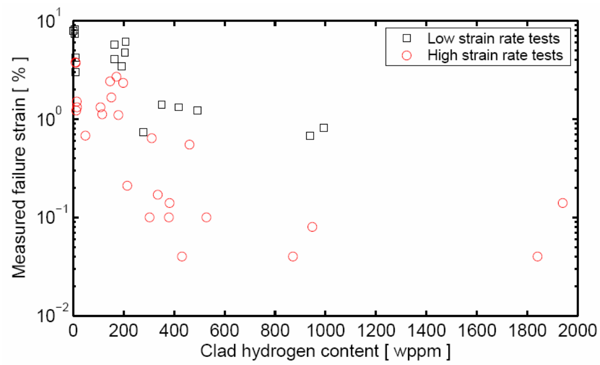

Figure 4. Clad failure strain vs. hydrogen content determined from tests on un-irradiated cladding at room temperature at low (<10^{-3} s^{-1}) and high hoop strain rate (>10^{-1} s^{-1}).

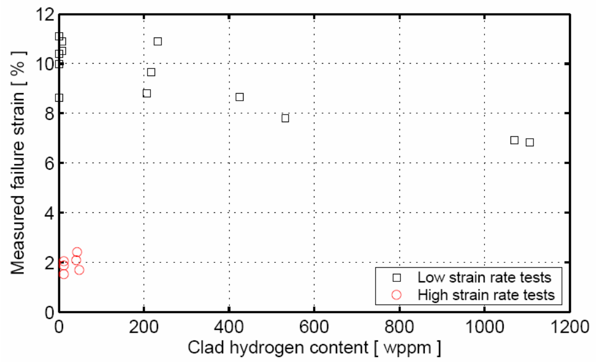

Figure 5. Clad failure strain vs. hydrogen content, determined from tests on un-irradiated cladding at temperatures between 523 and 673 K at low (<10^{-3} s^{-1}) and high hoop strain rat e(>10^{-1} s^{-1}).