doi:10.1017/S1431927622008145
Microsc. Microanal. 28 (Suppl 1), 2022
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Advanced Characterization of Fuel Cladding Chemical Interaction between U-10Zr Fuel and HT9 Cladding Tested in Fast Flux Test Facility

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Fuel cladding chemical interaction (FCCI) can greatly accelerate the cladding failure. However, due to the limited space in a fuel cladding assembly, it is historically challenging to gain an mechanistical understanding of the formation mechanism of FCCI and its influence on fuel and cladding performance. With the imminent need to qualify U-10Zr based metallic fuel cladded by HT-9 for advanced reactors demonstration project, it is of vital importance to use advanced characterization method to study FCCI in a unprecedent detailed manner and gain better mechanism understanding of FCCI.

Mechanistic Fuel Failure (MFF) series of prototypic fuel elements irradiated in FFTF [1, 2] provides the best samples to study FCCI since the MFF-series assemblies had an axial fuel height the same as proposed length by industry partners. Jason et al. [3] has performed preliminary post-irradiation examination on a MFF fuel pin sample, which was extracted from the HT9 cladded U-10at.%Zr MFF-3 pin MFF-3 pin (#193045) at an axial location of X/L = 0.98. This sample has a peak burnup of 5.7 at.% and peak inner cladding temperature (PICT) of around 615 °C during in-core testing. Scanning electron microscope examination has identified visible FCCI region on more than half of the HT9 circumference [3]. The most striking feature are grain boundary attacking by apparently lanthanides (Lns) rich phase. However, SEM cannot provide accurate assessment of phase and concentration of grain boundary phases and prevented a better understanding of the formation mechanism of such attach.

This study, by pairing transmission electron microscope (TEM) characterization and atom probe tomography (APT) techniques with in-situ micro-tensile testing in scanning electron microscope (SEM), aims at gaining in-depth understanding on the formed FCCI region. The identified FCCI region roughly consists of multilayers as illustrated in Figure 1 (c). The main findings are: (1) layer-B shows observable lanthanides (Lns) infiltration along grain boundaries and mechanical softening due to FCCI- and irradiation-induced microstructural and microchemistry changes, particularly the recovery of martensitic lath structure and dissolution of pre-existing $M_{23}C_6$ together with the formation of coarsened Laves phases, $(Fe, Cr)_2(Mo, W)$; (2) layer-C is Fe depleted but Lns significantly enriched, becoming very brittle; (3) layer-D is mainly composed of UFe_2 and Lns; (4) three FCCI-induced intermetallic U-Fe-Zr phases, χ ($Fe_{0.5}Zr_{0.32}U_{0.18}$), ε ($Fe_{0.3}Zr_{0.4}U_{0.3}$), λ ($Fe_{0.06}Zr_{0.23}U_{0.71}$), were identified near layer-E; (5) the χ ($Fe_{0.5}Zr_{0.32}U_{0.18}$) phase was characterized to be a face centered cubic (FCC) crystal structure.

These results will help to better understanding the governing mechanism of FCCI and facilitating the development of theoretical model for assessing the performance of metallic fuel and cladding integrity [4].

https://doi.org/10.1017/S1431927622008145 Published online by Cambridge University Press

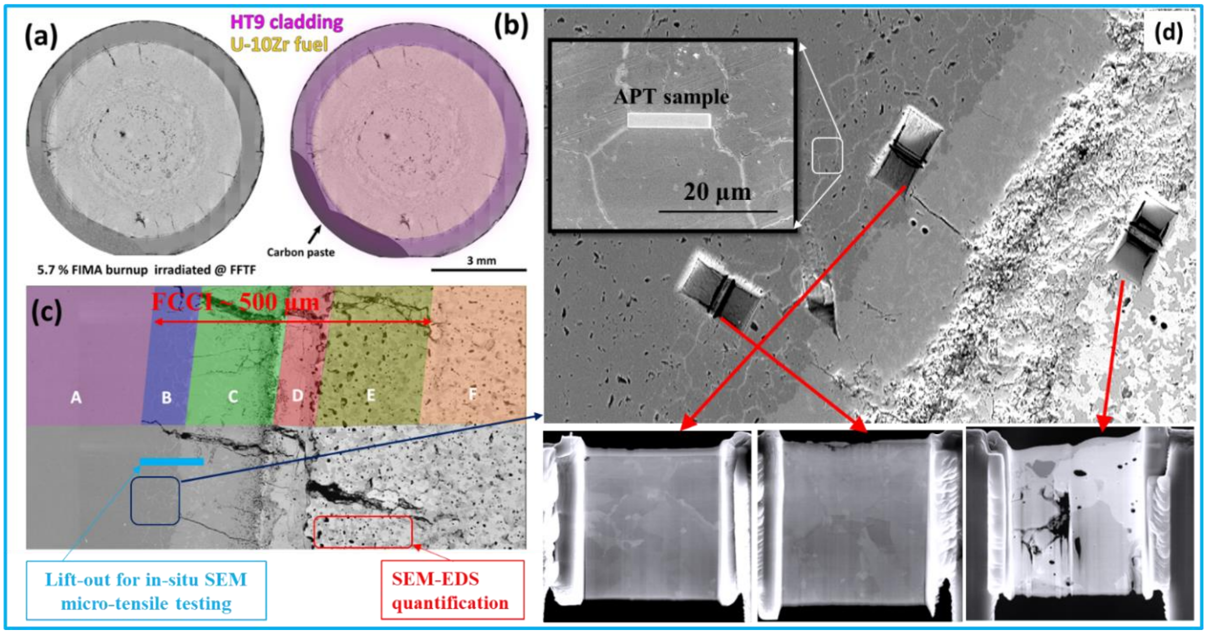

Figure 1. An illustration of samples prepared for advanced characterization of fuel cladding chemical interaction FCCI in a HT9 cladded U-10 at.%Zr fuel irradiated at FFTF. (a) A montaged BSE image showing the overall cross section microstructure of the examined sample. (b) A color-coded cross section image for (a). (c) A high magnification SEM image illustrating the distinguished layers in the FCCI region (including layer B-E) and marked the locations for characterizations. (d) An image showing locations for preparing TEM foils and APT samples.

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[4] Work supported through a INL Laboratory Directed Research& Development (LDRD, project 22A1059-094FP) and a Nuclear Science User Facilities Rapid Turnaround Experiment Proposal (NSUF-RTE, FY-2021 1st call, #4345) programs under DOE Idaho Operations Office Contract DE-AC07-05ID14517. We also acknowledge the partial support from US Department of Energy Advanced Fuel Campaign (AFC) Program.

https://doi.org/10.1017/S1431927622008145 Published online by Cambridge University Press