Deformation and Fracture Behaviors of Fe-Based Claddings for Accident-Tolerant Fuel under Fretting Wear Condition

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1. Introduction

FeCrAl alloys have been proposed as accident tolerant fuel (ATF) cladding because of their excellent oxidation resistance at high temperature and reasonable mechanical properties [1-3]. ATF cladding candidates including new materials and surface modification of Zr-based cladding shows outstanding oxidation resistance in high temperature steam [4-5]. This is because ATF candidates were selected based on the proven materials with excellent oxidation resistance at high temperature steam. In fuel assembly, however, fuel claddings are supported by grid spring and dimple and grid-to-rod fretting (GTRF) is known as one of the most important failure mechanisms by flow-induced vibration (FIV). Thus, fretting wear behaviors of ATF claddings against Zr-based spacer grid should be evaluated regardless of their outstanding oxidation resistance. In this study, fretting wear tests have been carried out to evaluate wear behaviors of two kinds of Fe-based cladding candidates (i.e., FCA rod and FCA coated Zr-based cladding by a cold spray method) focusing on the deformation and fracture behaviors of contact surfaces in room temperature water.

2. Experiments

The characteristics of cladding and grid materials used in this study are summarized in Table 1. A fretting wear tester was applied to evaluate wear behavior of Fe-based claddings and test conditions are summarized in Table 2. Details of this tester and sample arrays were illustrated in [6].

Table 1. Summary of tested cladding and grid samples

Samples	Label	Remarks
FeCrAl rod[7]	FCA	Fe-21.2Cr-5.2Al-0.15Mn-0.19Si-0.028C
Coated cladding	FCAC	FCA coated Zr-based cladding with cold spray w, w/o polishing
Grid	ArZr	As-received Zr-based grid
Oxidized grid	OxZr	Pre-oxidized Zr-based grid (180 days)

After fretting wear tests, wear volume and depth of Fe-based cladding are measured by a surface profiler. Also, each worn scar is observed using scanning electron microscope (SEM) to evaluate the mechanism of wear debris formation including the deformation and fracture of plastic deformation layer on worn surface.

Table 2. Summary of fretting wear test conditions

Rod	Grid	Variables
FCA FCAC	ArZr ArZr, OxZr	2~10N, 100~1k μm, 5~30Hz, RT water, up to 10^6 cycles

3. Results and Discussion

After the fretting wear tests, wear rates (wear depth increase per cycle) of test samples are calculated and summarized in Table 3. FCA condition shows rapid wear depth increase compared with FCAC condition. Interesting point is that FCA rod can accelerates the wear depth increase of Zr-based grid. In case of FCAC rod, however, wear rate is remarkably reduced due to the protective coating layer of Zr cladding, which have its relatively high bulk hardness. Also, oxide layer on grid spring is effective for improving wear resistance of the FCAC cladding.

Table 3. Wear rate results

Rod	Wear rate(μm/cycles)	Grid	Wear rate(μm/cycles)
FCA	77.7 x 10^{-6}	ArZr	135.6 x 10^{-6}
FCAC	22.5 x 10^{-6}	ArZr	N/A
FCAC	6.5 x 10^{-6}	OxZr	N/A

Fig. 1 shows typical morphologies of FCA worn surfaces after the fretting wear tests. Severe deformation layers are well developed and wear debris are generated by fracture of their edge regions, which act as third body abrasion between contact surfaces. Thus, similar bulk hardness values of two contact materials (FCA and Zr alloys) results in accelerated wear damages due to hard particles of FCA wear debris oxidation.

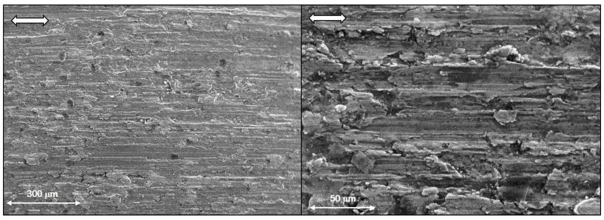

Fig. 1. Worn surface results of FCA rod against Zr-based alloy (2 N, 1 mm, 30 Hz, 10^6, RT water)

Fig. 2 shows worn surfaces of unpolished FCAC rod and Zr-based grid spring. FCAC has irregular coating layer and protruded area was worn out predominantly and it is difficult to find formation of surface cracks. Severe wear of Zr-based cladding is due to these hard parts, which results in excess contact stress. Thus, roughness of coating layer should be controlled to the level of commercial Zr-based cladding.

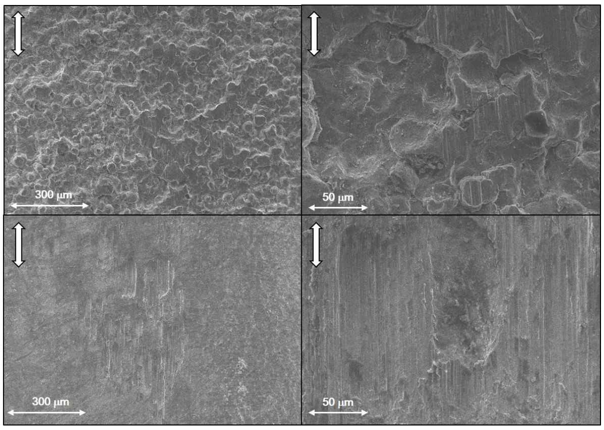

Fig. 2. Worn surface results of unpolished FCA-coated rod (Top) and Zr-based spacer grid (Bottom) at 10 N, 100 µm, 30 Hz, 10^6 and RT water.

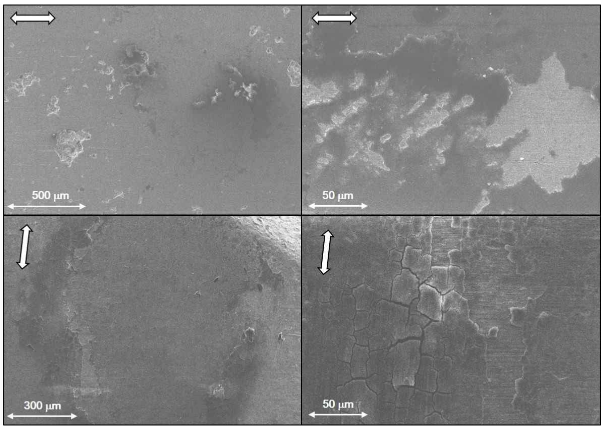

Fig. 3. Worn surface results of FCA-coated rod (Top) and pre-oxidized Zr-based spacer grid (Bottom) at 10 N, 100 µm, 30 Hz, 10^6 and RT water.

Fig. 3 shows fractured coating layer of polished FCAC rod and oxide layer of Zr-based grid spring under fretting wear tests. Thin coating layer of FCAC rod by post-polishing treatment can be easily fractured by hardened Zr-oxide layer of grid spring and need to improve the interfacial joining strength between FCA coating and Zr matrix. Interesting point is that oxide layer of Zr-based grid spring also was degraded by formation of multi-cracks and fracture. This result indicates that wear and corrosion damages of grid spring can be accelerated in normal operations and the inherent function of spacer grid can be lost in a relatively short time. Therefore, new spacer grid materials or design changes should be considered when current Zr-based cladding is replaced by FCA or FCA-coated cladding.

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