Development Status of Surface-Modified Fuel Cladding for ATF

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1. Introduction

Zr-based alloys have been used as fuel cladding in nuclear reactor for a long time, because they have good corrosion resistance and mechanical properties and neutron economy in normal operation conditions. However, enhanced accident tolerant fuel (ATF) cladding has been in development by nuclear operators since the Fukushima accident [1-3]. Enhanced ATF cladding can be defined as cladding that provides considerably increased response time in the event of a nuclear reactor accident, while providing performance similar to or better than that of the commercial Zr cladding during normal operation [1-3]. In addition, an enhanced accident tolerance includes suppressed reaction with steam, resulting in lower hydrogen generation, while maintaining acceptable cladding geometry by increasing the strength during accidents. In light water reactors (LWRs), the fuel cladding should have excellent heating transfer and corrosion resistance characteristics, while preventing primary leakage of the fission products in fuel pellet.

After considering the various ATF cladding concepts and technologies, Korea Atomic Energy Research Institute (KAERI) focused on surface-modified Zr cladding as a near-term application [6]. The major benefit of the surface-modified Zr cladding concept or coated cladding [7] is the economics when compared to other concepts such as FeCrAl cladding [8], Mo-lined cladding [9], and SiCf/SiC cladding [10], because the commercial Zr-based alloy and manufacturing facility can be used continuously. However, the surface-modified Zr and cladding coating concepts require the development of coating materials and coating technology. This study focused on the performance evaluation of the surface-modified Zr cladding.

2. Methods and Results

Regarding the fuel cycles shown in Fig. 1 [4], the manufacturing technology of Zr cladding and strips has been established in the industry because of the accumulation of manufacturing technologies during recent decades. In normal operation conditions, the major requirements, such as corrosion, creep, irradiation growth, and wear, generally are satisfied using commercial Zr alloy cladding.

Performance parameters		Commercial Zr alloy cladding
Manufacturability		• Optimized
Normal condition	Corrosion	• No problem (Oxide Thickness <100mm)
	Creep	• No problem (Hoop Strain<1%)
	Irradiation growth	• No problem (Shoulder gap closure)
	Wear resistance	• No problem (Wear damage < 10% in thickness)
	PCMI/PCI	• PCMI/PCI failure related to the hydride (hydrogen pick-up by corrosion)
DBA	LOCA	• Severe oxidation and hydrogen generation • Ballooning & Burst • Limitation (PCT<1204°C, ECR<17%)
	RIA	• PCMI failure related to the hydride
BDBA		• Severe oxidation and hydrogen generation • Melting problem
Spent fuel storage	Failure mechanism	• Brittle behavior by hydride • Hydride re-orientation problem (Fuel-clad interface temp.; drying: <570°C, storage: <400°C) (Clad hoop stress; <90MPa)

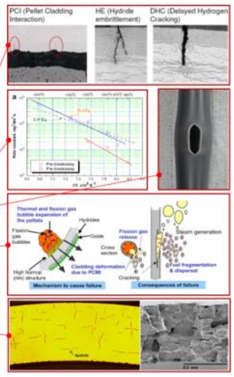

Fig. 1. Summary of the performance parameters of commercial Zr alloy cladding as a function of the fuel cycles from the fabrication to storage steps [4]

However, embrittlement problems associated with hydrogen uptake in to the Zr alloy cladding matrix by a corrosion reaction remain unresolved in normal and design basis accidents (DBAs). In accident conditions, various issues, such as high-temperature oxidation, ballooning and burst, and low ductility after accidents, are significant problems in the Zr alloy cladding. The development of advanced Zr-based alloys enables performance in normal conditions to improve when compared with the Zircaloys; whereas performance at high temperatures does not considerably improve due to the material limitation of Zr alloys. In addition, the possibility of cladding failure during spent fuel storage is a pending issue because of hydride reorientation [5]. After consideration of these problems, it is clear that the ATF cladding must meet all the conditions of the nuclear fuel cycle as well as performance requirements during accidents. New concepts of cladding have to include for the feasibility assessment regarding the fuel performance code, economic, operational safety, and environmental impacts. New ATF cladding concepts require feedback form utilities and vendors on the acceptability of the design and expected performance. The challenges to develop ATF cladding results from the maturity of the technology.

Table 1 shows the test cladding of four conditions made by combining the technology under development at KAERI. In the surface modified-Zr cladding concept, the samples were manufactured by applying two coating methods such as arc ion plating and 3D laser coating. More importantly, the oxidation resistance material coating is possible in both the two methods, the latter method is only possible for the reinforcement treatment (oxide dispersion strengthened, or ODS). Basically, there are two materials for the oxidation resistant coating, one is an FeCrAl alloy manufactured by Sandvik (APMT; Fe-22Cr-5Al-3Mo in wt.%) and the other is an CrAl binary alloy. The CrAl binary alloy (Cr-15Al in wt.%) was designed by KAERI to have excellent corrosion resistance under normal conditions as well as accident conditions.

Table I: Summary of candidate surface-modified Zr cladding for ATF cladding in KAERI [4]

Type	Partial ODS		Coating		Remarks (target)
	oxide type	method	material	method	
1	-	-	CrAl	Arc ion plating	Corrosion
1-1	Y_2O_3	Laser beam scanning	CrAl	Arc ion plating	Strength and Corrosion
2	-	-	Cr/FeCrAl	Arc ion plating for Cr, 3D laser coating for FeCrAl	Corrosion
2-1	Y_2O_3	Laser beam scanning	Cr/FeCrAl	Arc ion plating for Cr, 3D laser coating for FeCrAl	Strength and corrosion

- *Thickness of partial ODS layer ranged from 80 to 120 micron*
- *Thickness of CrAl coated layer ranged from 40 to 60 micron*
- *Thickness of Cr coated layer ranged from 10 to 20 micron*
- *Thickness of FeCrAl coated layer ranged from 40 to 60 micron*

A comprehensive evaluation of the cladding performance is important from a licensing and commercialization point of view. Therefore, the performance evaluation of the cladding should consider the criteria that applied to existing cladding development. In addition, in the case of enhanced ATF cladding, there are other factors to consider depending on the concept. For surface-modified Zr cladding, verification of the adhesion and performance properties of the surface treatment layer is very important.

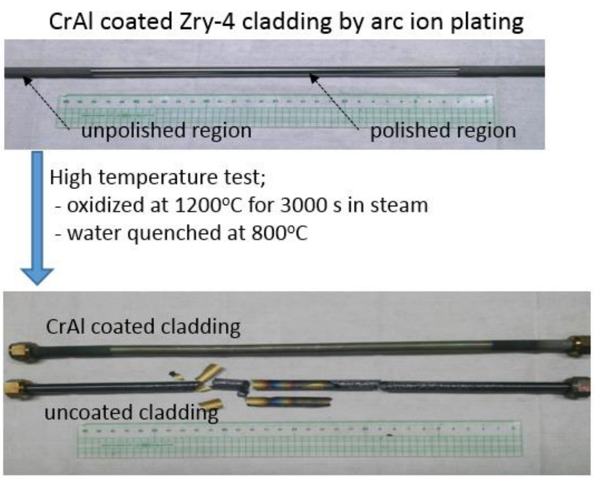

Fig. 2. High temperature oxidation and water quenching behavior of CrAl coated Zry-4 cladding and uncoated Zry-4 cladding

Fig. 7 shows the evaluation of the high temperature oxidation properties of the CrAl-coated Zry-4 cladding by arc ion plating, using uncoated Zry-4 cladding as a reference. Because the coating is applied only on the outer surface, the oxidation test of two specimens was focused on the outer surface of the tube. When the prepared specimens were maintained at 1200oC for 3000 s in a steam environment and cooled to 800oC and then water quenched, the CrAl-coated Zry-4 cladding remained without damage, while uncoated Zry-4 cladding was damaged severely by thermal shock.

To summarize the various performances, the surface-modified Zr cladding shows the improved performance (corrosion/oxidation, creep, wear, LOCA) and shows the reasonable performance (welding) when compared to commercial Zr cladding. Regarding the corrosion behavior, the flaking or galvanic corrosion was not observed in the samples between Zr matrix and coated material interface, which can be identified form the corroded sample appearances. A good corrosion/oxidation resistance of the CrAl binary alloy is the result of the stable oxide formations by an optimized compositional ratio between Cr and Al. It is confirmed that $CrAl_2O_4$ phase is stabilized under the normal operation condition and accident conditions. Improved mechanical properties such as creep and wear resistance were shown in the surface-modified Zr cladding, because the CrAl alloy had a higher strength than Zr alloy as well as the ODS structure layer had a good strength up to high temperatures. At the high-temperature, cladding strength is considerably improved by a uniform distribution of the Y_2O_3 particles although the thickness of ODS layer was 100 microns. An irradiation test of the surface-modified Zr cladding was reached up to 360 FPD (burnup: 16.2MWd/kgU) in Halden research reactor. During the operating period so far, the KAERI rods have operated normally and without any indication of failure.

3. Conclusions

After reviewing various ATF concepts, the KAERI selected a surface modification technology on a commercial Zr alloy. Surface modification technology can be defined as CrAl coating using arc ion plating for enhanced oxidation resistance and ODS using 3D laser scanning for high temperature strength enhancement. Surface-modified specimens were fabricated, and performance tests were conducted under normal and accident conditions. The increase of corrosion resistance in normal and accident conditions of surface-modified Zr cladding was confirmed by the coating of CrAl alloy, which had good corrosion resistance. The improvement of creep and high-temperature deformation resistance was largely achieved by strengthening by ODS treatment, and the improvement of wear resistance was caused by the physical properties of the CrAl coating layer. No significant damage occurred at the interface between the CrAl coating layer by arc ion plating and the zirconium material during severe deformation and corrosion/oxidation tests. Because of these out-of-pile tests, surface modification technology was shown to have sufficient potential as an ATF cladding.

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