Development Status of Accident Tolerant Fe-based Alloy Cladding at KEPCO NF (in collaboration with KAIST)

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1. Introduction

Since December 2017, KEPCO NF has started to develop nuclear fuel cladding with improved accident tolerance. Two kinds of concept were selected as the material for candidate accident tolerant fuel (ATF) claddings. One is to apply special treatment on the surface of Zr-based alloy cladding. The surface of Zr-based alloy cladding tube is alloyed with oxide particles by 3D laser technique to increase the mechanical strength of cladding. And, the surface-treated layer is coated with an oxidation resistant material in normal and accident conditions of light water reactors. These surface improvement technologies is currently being developed by KAERI and will be applied to advanced Zr-based alloy tube developed by KEPCO NF [1].

The other is to develop new Fe-based alloy as a cladding material to replace the existing Zr-based alloy cladding. Fe-based alloys had been used as materials for the nuclear fuel in the past, and are currently being used in various regions of nuclear reactors such as internals. Since this concept can be applied as a monolithic cladding material rather than two- or three-layer coated cladding, it would give a simplicity to the nuclear fuel design as well as long-term storage of spent fuel rod. In addition, it is possible to solve potential concerns by replacement of Zr material such as the hydrogen generation by Zr oxidation and their embrittlement in accident conditions. The alloy design and fabrication process development for a new Fe-based alloy is performed at KEPCO NF and KAIST. And, fabrication technology of thin tubes is currently being developed by Shinhan Metal Co., LTD.

In this presentation, the current development status of Fe-base alloys and future plan will be introduced.

2. Methods and Results

2.1 Alloy Design and Manufacturing Process

The main purpose developing the newly designed Fe-based alloys are to increase the strength and reduce the reaction rate with high temperature steam. In addition, during the normal operation, the dissolution of Fe ions into the coolant by corrosion should be minimized. The alloy design was performed based on Fe-Cr-Al (FeCrAl) alloy which are developed for ATF cladding in US and Japan [2-4]. The alloying elements currently being considered are nickel with minor elements. Two Fe-based alloys named as Alumina-forming Duplex Stainless Steel (ADSS) and Advanced Ferritic Steel (AFS) were designed. The design of ADSS and its performance in normal and accident conditions were described in detail [5]. And, the current status of AFS alloy design and its characterization that is another candidate Fe-based alloy is described in this paper. Two batches of AFS were fabricated with various manufacturing processes after ingot fabrication using vacuum arc melting (VAM) and vacuum induction melting (VIM) methods. Up to now, all of the AFS alloys were fabricated by warm rolling. Two candidate AFS alloys were successfully manufactured to thin plate by cold rolling. The alloy compositions and manufacturing process are being currently optimized to improve the productivity of AFS alloy.

2.2 Performance Evaluation

To evaluate the performance of test alloys, the high temperature steam oxidation tests, tensile tests, and corrosion tests in normal and accident conditions were performed. The high temperature steam oxidation tests were conducted at 1200 °C in Ar/steam mixed environment. As shown in Fig. 1, the test results showed that the oxidation weight gain of test alloys were much lower than commercial Zr-based alloys (about 1000 X). The corrosion tests were performed in a simulated PWR water. The corrosion weight change of AFS alloys was decreased by a factor of 2 when compared with a commercial FeCrAl alloy.

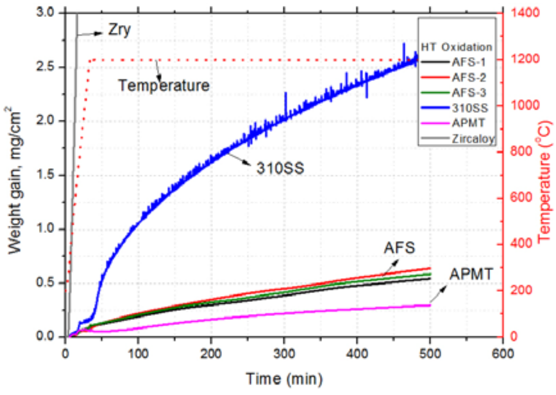

Fig. 1. Oxidation test results of AFS alloys tested in 1200 °C Ar/steam mixed environment.

2.3 Fabrication of Thin Tubes

The manufacturing technology of thin tube using Fe-based alloys is a necessary technique for use as fuel cladding materials. Up to now, although much of efforts have been paid to develop the manufacturing thin FeCrAl alloy tube with 4 m length, it does not successfully manufactured in the world [2-4]. Therefore, the 4 m long tube manufacturing technology is one of the most challenging items in the development of Fe-based alloy cladding. In order to facilitate the development of domestic manufacturing technology of thin tube, we are trying two approaches. One is to collaborate closely with domestic tube manufacturing company that has pilger machine and abundant manufacturing experience in high strength alloy tube. Second our strategy is to collaborate with an overseas company that has a lot of experience of thin tube manufacturing using similar alloys.

In order to evaluate the feasibility of producing thin tubes of Fe-based alloys, a master bar of FeCrAl alloy were used for trial manufacture in cooperation with overseas precision tube manufacturing company. In results, as shown in Fig. 2, two thin tubes of FeCrAl (the chemical composition was 24 wt.% Cr and 5.4 wt.% Al) were successfully manufactured. The maximum length of tubes was 1.9 m and the thickness of tubes were 0.35 mm ± 0.0024 mm.

After the successful fabrication of FeCrAl alloy tube, the thin tube by using two candidate Fe-based alloys, ADSS and AFS will be fabricated. Our target dimension of the tube is 9.5 mm OD, 0.35 mm t, and 4 m length.

	A	B	C	D	E	F	G	H
Thickness(μm)	352	349	356	350	352	348	352	352

Fig. 2. Photo of FeCrAl tube fabricated by pilgering with a dimension of 9.5 mm OD x 0.35 mm t x 1.9 m L.

2.4 Nuclear Fuel Design - Preliminary

Compared with Zr-based alloy cladding, it was known that one of the main challenging issues of Fe-based alloy is their higher neutron absorption cross-section. To reduce the neutron penalty of these alloy in similar level to the current nuclear fuel cycle, the thickness reduction of tube and increase in the enrichment of U-235 are necessary. These two parameters will be carefully selected considering the economics of nuclear fuel cycle and the soundness of cladding in normal and accident conditions.

Table I shows the difference of effective full power day (EFPD) of two Fe-based candidate alloys with cladding thickness of 0.35 mm compared to that of current Zr-UO_2 fuel. Two pellet diameters was used as variables, with the pellet size of current fuel system and the increased pellet diameter to compensate the extra space by the thickness reduction of cladding with constant cladding outer diameter (9.5 mm). The enrichment of U-235 was slightly increased from current U-235 enrichment (4.65 % → 4.95 %). As shown in Table I. The EFPD of two candidate cladding materials were markedly reduced from current fuel cycle length when the pellet diameter and enrichment are not changed. On the other hand, when the pellet diameter is increased (with constant clad-pellet gap size) and the U-235 enrichment is increased to 4.95 % (less than 5 % enrichment limit), the EFPD were similar to current fuel cycle length (less than ± 5 days) in both of candidate materials. Therefore, with cladding thickness of 0.35 mm and U-235 enrichment of 4.95 %, the fuel cycle length of two candidate Fe-based alloy cladding could be comparable to that of current Zr-UO_2 fuel.

These results shows a preliminary evaluation results and does not show the accurate core analysis results. In the future, nuclear fuel cycle evaluation with Fe-based alloys will be evaluated in more detail, as well as fuel rod performance during the normal and transient conditions and safety analysis in accident conditions.

Table I: Difference of effective full power day (EFPD) of two candidate Fe-base alloys with cladding thickness of 0.35 mm compared to that of current Zr-UO_2 fuel

U-235 Enrichment	4.65 %		4.95 %	
UO_2 dia. (mm)	Current pellet size	Increase in pellet dia.	Current pellet size	Increase in pellet dia.
ATF-1 (days)	-109.3	-54.4	-53.9	-4.7
ATF-2 (days)	-99.9	-45.2	-44.3	4.84

3. Conclusions

KEPCO NF (in collaboration with KAIST) has started to develop accident tolerant nuclear fuel cladding material having high applicability and excellent performance in normal and accident conditions. The alloy design and manufacturing process are now being optimized. The results of trial tube manufacture of commercial FeCrAl alloy showed that the fabrication of the thin tube of candidate Fe-based alloys developed by KEPCO NF and KAIST are feasible by pilgering process. In addition, the results of preliminary fuel cycle length evaluation showed the Fe-based alloy could be applied as a cladding material of nuclear fuel with marginal modification of cladding thickness (same outer diameter) and slightly increase of U-235 enrichment (less than 5 wt.% enrichment limit).

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