# Progress of Accident Tolerant Fe-based Alloy Cladding Development at KEPCO NF

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## 1. Introduction

KEPCO NF selected advanced Fe-base alloys as one of the candidate materials of accident tolerant fuel (ATF) claddings. 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. This monolithic cladding concept rather than two- or three- layer coated cladding would give a simplicity to the nuclear fuel design as well as long-term storage of spent fuel rod. It is possible to completely solve the potential concerns such as the hydrogen generation by Zr oxidation and their embrittlement when the coated layer is peeled off. The alloy design and fabrication process development for a new Fe-based alloy is performed at KEPCO NF in collaboration with KAIST. And, fabrication technology of thin tubes is currently being developed by KEPCO NF and a domestic tube manufacturer (Shinhan Metal Co., LTD).

Development status of Fe-base alloy and future plan were presented at 2018 KNS fall meeting [1]. Two Fe-base alloys named as alumina-forming duplex stainless steel (ADSS) and advanced ferritic steel (AFS) are considered as candidates. The development status of ADSS and AFS was described in terms of out-of-pile performance, tube manufacturing, and neutronic properties [1,2]. In this paper, the advance in ADSS and AFS development were updated.

## 2. Methods and Results

### *2.1 Performance Evaluation*

The high temperature steam oxidation tests, tensile tests, and corrosion tests of ADSS and AFS alloys 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 oxidation weight gains of AFS alloys were much lower than commercial Zr-based alloys (The weight gain of ADSS alloy was similar with those of AFS alloys). In addition, ADSS and AFS alloys showed much higher tensile strength compared to commercial FeCrAl as shown in Table I. And, the corrosion weight change of ADSS and AFS alloys in a simulated PWR environment was lower by a factor of 2 when compared with a commercial FeCrAl alloy (It is not shown in this paper). As a consequence, it is thought that the AFS alloys satisfies the major properties to be required as nuclear fuel cladding.

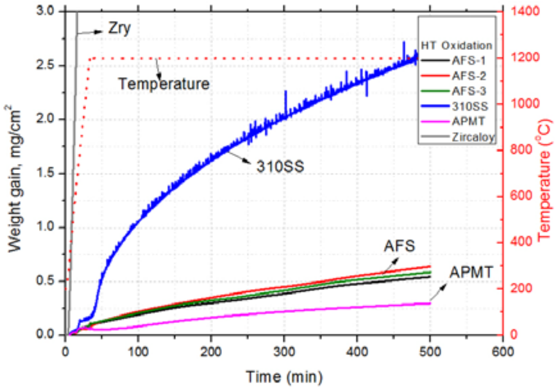


Fig. 1. Oxidation test results of AFS alloys tested in 1200 °C Ar/steam mixed environment.

Table I: Tensile properties of Fe-based alloys at room temperature.

| | ***ADSS*** | **AFS** | **FeCrAl** |
|---|---|---|---|
| YS(MPa) | 816 | 651 | 492 |
| UTS(MPa) | 1,134 | 774 | 701 |
| Elong.(%) | 20 % | 18% | 25 % |

### *2.2 Fabrication of Thin Tubes*

The manufacturing technology of thin tube using Fe-based alloys is a necessary technique for use as fuel cladding materials. Due to their hard workability, 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. First is to collaborate closely with domestic tube manufacturing company that has pilger machine and abundant manufacturing experience in high strength alloy tube. The second our strategy is to collaborate with an overseas company that has a lot of experience of thin tube manufacturing using similar alloys.

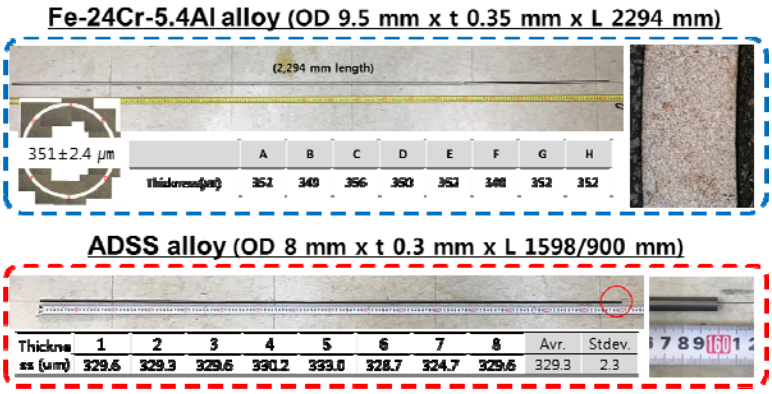


Fig. 2. Photo of FeCrAl tube fabricated by pilgering with a dimension of 9.5 mm OD x 0.35 mm t x 1.9 m L.

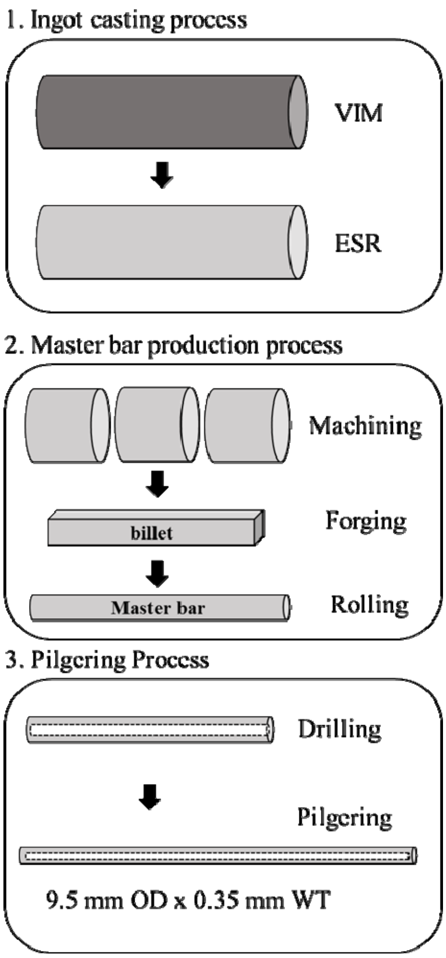


Fig. 3. Thin tube manufacturing process for ADSS and AFS.

Trial-manufacturing of FeCrAl (the chemical composition was 24 wt.% Cr and 5.4 wt.% Al) alloy and ADSS alloy have been successfully performed at overseas company as shown in Fig. 2. For FeCrAl tube, the maximum length of tubes was 1.9 m. And the thickness of tubes were 0.35 mm ± 0.0024 mm. For ADSS tube, the maximum length was 1.6 m. And the thickness of tubes were 0.30 ± 0.0023 mm. Based on these successful trial-manufacturing experience, the thin tube of two candidate Fe-base alloys (ADSS and AFS) are now being manufactured. The manufacturing process for thin tube is given in Fig. 3. ADSS alloy and Two AFS alloys were manufactured in 600 ~ 700 kg scale. And then, the ingots were hot-forged and rolled for manufacture of the master bar. During hot-forging, the ADSS billet was failed. But, two AFS alloy ingots were successfully manufactured to master bar. The AFS master bar was sent to tube manufacturer. Thin tubes of AFS having 4 m in longitudinal, 9.5 mm in outer diameter, and 0.35 mm in thickness will be manufactured by end of May, 2019.

### *2.3 Nuclear Fuel Design*

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.

From our preliminary evaluation [1], with 4.95 % of U-235 enrichment, the fuel cycle length of Fe-base alloy claddings was similar with that of current fuel system [1]. However, this simple calculation was preliminary evaluation results and did not show the accurate results.

To investigate more accurate impact of Fe-base alloys on fuel cycle length, the power density change due to increase in pellet size and fuel cycle length change in each cycle are considered in a simplified fuel assembly calculation. The fuel assembly used for this calculation was PLUS7 that is currently used in OPR1000 and APR1400. Fig. 4 shows the difference of $K_{inf}$ value of $UO_2$/ADSS cladding compared to $UO_2$/Zr cladding. The dimension of $UO_2$/ADSS cladding were follows; the cladding thickness was reduced to 0.35 mm.

And, $UO_2$ pellet diameter was increased to 8.632 mm to maintain the same pellet-cladding gap size with current $UO_2$/Zr cladding. The increase in pellet diameter could give not only the large amount of neutron absorption by U-238 but also the large amount of fission by U-235. As a results of these competitive reaction, at the beginning of cycle (BOC), the large reduction of $K_{inf}$ was observed. But, with increase of fuel cycle, the difference of $K_{inf}$ was significantly reduced.

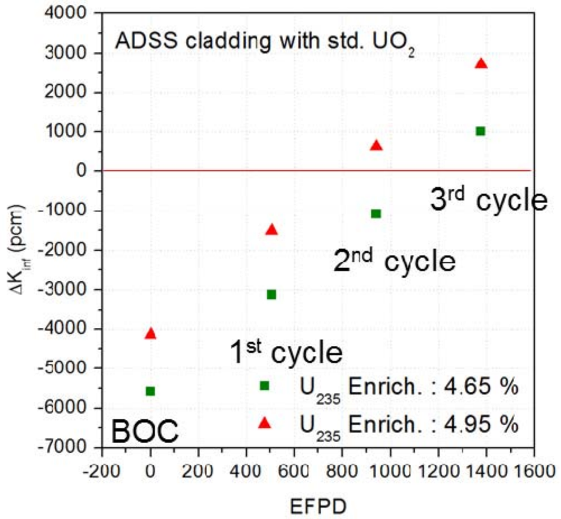


Fig. 4. The difference of multiplication factor of ADSS cladding with 0.35 mm thickness compared to current UO2/Zr fuel system.

Table I shows the difference of ADSS alloys with cladding thickness of 0.35 mm compared to that of current Zr-$UO_2$ fuel. As shown in Table I. The large reduction of EFPD at 1st cycle was observed but the difference of EFPD was markedly decreased at 3rd cycle, which is similar results observed in Fig. 4. Thus, in case of 4.65 wt.% U-235 enrichment, the total reduction of EFPD due to ADSS cladding can be calculated by sum of the difference of EFPD at each cycle (-106 days). On the other hand, when the U-235 enrichment is increased to 4.95 % (less than 5 % enrichment limit), the EFPD of ADSS cladding for three cycles was higher than current fuel cycle length (61 days). Therefore, by reducing cladding thickness to 0.35 mm and slight modification of U-235 enrichment, the fuel cycle length of Fe-base alloy cladding could be comparable to that of current Zr-$UO_2$ fuel.

Table II: Difference of effective full power day (EFPD) of ADSS cladding with cladding thickness of 0.35 mm compared to that of current Zr-$UO_2$ fuel

| *U enri.* | *1st cycle* | *2nd cycle* | *3rd cycle* |
|---|---|---|---|
| 4.65 wt.% | -104 | -36 | 34 |
| 4.95 wt.% | -50 | 21 | 90 |

## 3. Conclusions

KEPCO NF (in collaboration with KAIST) has selected Fe-base alloy as a candidate ATF cladding material having high applicability and excellent performance in normal and accident conditions. The alloy design and manufacturing process are now being optimized. Based on successful trial tube manufacture of Fe-base alloys, the large-scale tube manufacturing is ongoing. In addition, the fuel cycle length could be adjustable to that of current $UO_2$/Zr fuel system through the marginal modification of cladding thickness (same outer diameter) and slightly increase of U-235 enrichment (less than 5 wt.% enrichment limit).

## 4. Acknowledgements

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