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Development Status of Advanced Ferritic Steel for Accident Tolerant Fuel Cladding

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1. Introduction

In the past, nuclear fuel used in nuclear power plants focused on maintaining long-term integrity in the neutron irradiation and hydrochemical environments. However, after the Fukushima nuclear power plant accident, researches have been actively conducted to develop nuclear fuel with superior accident safety as called accident tolerant fuel (ATF). It has been developed with the concept of increasing the coping time in accident condition while maintaining the performance of the existing nuclear fuel [1-2]. Fe-based alloy was candidates for ATF, this alloy based on the FeCrAl alloy, which has been used as a heating element at high temperatures traditionally [3-6].

Since December 2017, KEPCO Nuclear Fuel has started to develop ATF and Advanced Ferrtic Steels(AFS) was researched as one of the candidates for ATF cladding [7]. In this study, the Fe-based alloy was designed to improve the accident tolerance, and the performance evaluation was conducted through corrosion test in normal operation conditions and the high temperature oxidation test in accident conditions. Furthermore, manufacturing test based on commercial manufacture of candidate alloys was performed.

2. Methods and Results

2.1 Alloy Design

The AFS alloy were consisted of Fe, Cr, Al, Ni, Si, C, Mn and Y. In order to select the compositions of the candidate alloy, 14 preliminary test alloys were prepared in button form of 200 g ingot by using the arc melting furnace. The amount of alloying element was controlled in the AFS so that the matrix was maintained the ferrite structure up to the melting temperature as not deteriorate the mechanical properties due to phase transformation. It is designed to retain good corrosion resistance by forming Cr oxides in normal operation conditions and to improve the high temperature oxidation resistance by Al oxides in accident conditions. However, in the case of Fe-based alloy, the neutron absorption cross-section is higher than existing zirconium alloys. So, cladding tube was required to reduce the thickness about ~40% for the neutron economy. Therefore, Ni was added to increase the strength to secure structural integrity of the cladding tube. When a small amount of Ni was added, solid solution strengthening was expected. And when a large amount of nickel was added, Ni-Al intermetallic compounds were precipitated at the matrix, as shown in Fig. 1.

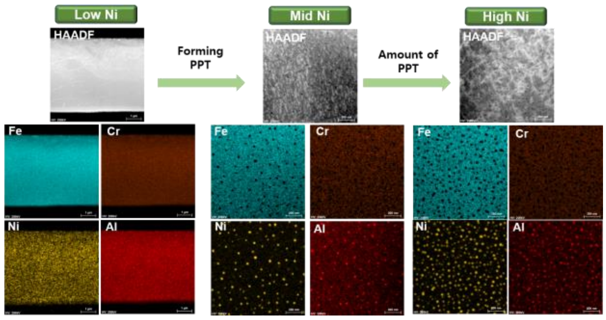
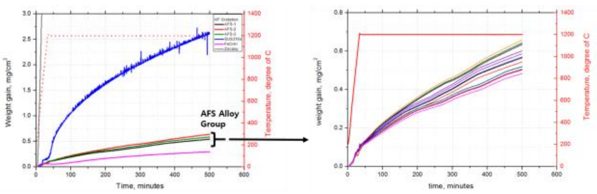


Fig. 1. Precipitations forming behavior according to nickel addition

2.2 Performance Evaluation

The high temperature oxidation and corrosion properties was evaluated to derive the candidate alloys. The high temperature oxidation tests were conducted using TGA at 1200 °C and 8 hours in steam-argon mixed environment. As shown in Fig. 2-(b), Similar high temperature oxidation resistance results were obtained in the composition range of AFS preliminary test alloys. The weight increase due to high temperature oxidation showed about 1000 times less than the existing zirconium alloy and Kanthal APMT and SUS310s were used as reference Fe-based alloy, the results were shown in Fig. 2-(a).



(a) (b)

Fig. 2. Results of high temperature oxidation at 1200 °C

And normal operation corrosion test was conducted at 360 °C and 190 bar in simulated primary water chemistry of the pressurized water reactor. Figure 3 shows the results of the corrosion test in the simulated primary water environment for 77 days. As a results of comparison between FeCrAl alloy and alloy containing small amount of Ni, it was observed that the weight loss was significantly reduced with presence of nickel.

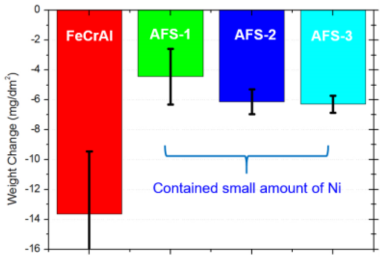


Fig. 3. Results of corrosion test for normal operation

2.3 Manufacturing

Prior to the test fabrication of AFS alloy, the preliminary test manufacturing was carried out using commercial FeCrAl alloy which is manufactured in China. As shown in figure 3, the commercial FeCrAl alloy was manufactured successfully, and the maximum length of tubes was 1.9 m and the thickness of tubes were 0.35 mm ± 0.0024 mm.

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

Fig. 4. Photographs of FeCrAl tube fabricated by pilgering with a dimension of 9.5 mm OD x 0.35 mm t x 1.9 m L

In order to establish the manufacturing process of AFS alloy, the test manufacturing was carried out on the laboratory scale and pilot scale. In manufacturing process, the master bar was manufactured by using an ingot production, heat treatment, hot forging and hot rolling, and the tube was manufactured the pilger method. On laboratory scale, 50 kg ingots were prepared by vacuum induction melting of for candidate alloys. Also, 1 ton ingots were manufactured on the commercial scale to prepare the master bar. Currently, the tube manufacturing process is being performed.

3. Conclusions

In this study, alloy design, performance evaluation and manufacturing process development were performed for Fe-based alloy which is one of the ATF candidates. Two candidate alloys have been derived from 14 AFS preliminary test alloys, and final candidate alloys will be derived in near future. The AFS alloy showed less dissolution due to corrosion in PWR environment compared to commercial FeCrAl.

4. Acknowledgements

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REFERENCES

[1] S. J. Zinkle, K.A. Terrani, J.C. Gehin, L.J. Ott, L.L. Snead, Accident tolerant fuel for LWRs: A perspective, Journal of Nuclear Materials, Vol. 448 p. 374–379. 2014.

[2] B.A. Pint, K.A. Terrani, M.P. Brady, T. Cheng, J.R. Keiser, High Temperature Oxidation of Fuel Cladding Candidate Materials in Steam–hydrogen Environments, Journal of Nuclear Materials, Vol. 440 p. 420–427, 2013.

[3] Y. Yamamoto, B.A. Pint, K. A. Terrani, K.G. Field, Y. Yang, L.L. Snead, Development and Property evaluation of nuclear grade wrought FeCrAl fuel cladding for light water reactors, Journal of Nuclear Materials, Vol.467, p. 703-716, 2015.

[4] R. Rana, C. Liu, R.K. Ray, Low-density Low-carbon Fe–Al Ferritic Steels, Scripta Materialia, Vol. 68, p.354–359, 2013.

[5] J. Klöwer, High Temperature Corrosion Behavior of Iron Aluminides and Iron-aluminium-chromium Alloys, Materials and Corrosion Vol. 47 p.685–694, 1996.

[5]K.G. Field, M.N. Gussev, Y. Yamamoto, L.L. Snead, Deformation Behavior of Laser Welds in High Temperature Oxidation Resistant Fe–Cr–Al alloys for fuel Cladding Applications, Journal of Nuclear Materials, Vol. 454 p. 352–358, 2014.

[6] K.G. Field, X. Hu, K.C. Littrell, Y. Yamamoto, L.L. Snead, Radiation Tolerance of Neutron-irradiated Model Fe–Cr–Al Alloys, Journal of Nuclear Materials, Vol. 465 p.746–755, 2015.

[7] H. Jang, S.Y. Lee, D.G. Ko, C.Y. Lim, Y.H. Kim, S.J. Lee, Development Status of Accident Tolerant Fe-based Alloy Claddding in KEPCO NF, Transactions of the Korean Nuclear Society Autumn Meting, October 25-26, 2018, Yeosu, Korea.