*Transactions of the Korean Nuclear Society Autumn Meeting*
*Yeosu, Korea, October 25-26, 2018*

# Design and Evaluation of Advanced Ferritic Steel for Accident Tolerant Fuel Cladding

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## 1. Introduction

The FeCrAl (Iron-Chromium-Aluminum) alloys have been used as high-temperature heating element. Recently, these alloys were considered as one of the candidates for accident tolerant fuel cladding materials in light-water reactors due to their superior properties such as good corrosion resistance in normal operation state [1-3] and excellent high temperature oxidation resistance in transition and accident environments, compared with commercial zirconium alloys [4-8].

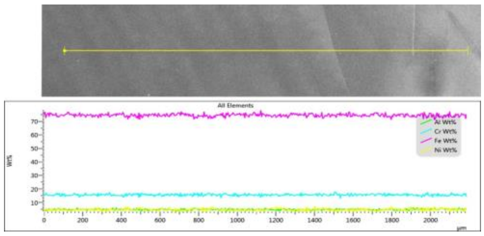
In recent years, KEPCO NF have started to develop advanced ferritic steels (AFS) that are containing Cr, Al, Ni and small amount of minor elements as alloy elements. In this study, the effects of alloying composition and heat-treatment conditions on workability and microstructural characteristics of AFS were investigated. In addition, the normal operation corrosion behavior and high temperature steam oxidation resistance of AFS alloys were investigated.

## 2. Experimental Procedures

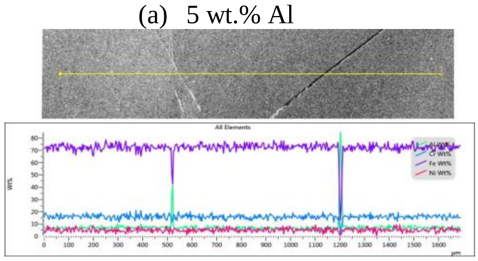
The AFS alloy compositions were consisted of 13 ~ 18 wt.% chromium, 5 ~ 7 wt.% aluminum and 0 ~ 10 wt.% nickel. The addition of nickel was expected to increase the high temperature strength by solid solution and forming B2(Ni-Al) intermetallic precipitate. These alloys were cast by vacuum arc melting method and the plate specimens were prepared though homogenization heat treatment, hot rolling, intermediated heat treatment, cold rolling and final annealing heat treatment. The workability was evaluated from the processing yield % in hot rolling stage. The high temperature oxidation tests were conducted using TGA at 1200 ºC and 8 hours in steam-argon mixed environment. And normal operation corrosion test was conducted at 360 ºC and 190 bar in simulated primary water chemistry of the pressurized water reactor.

## 3. Results and Discussions

As a first step of workability evaluation of AFS alloys, it was conducted whether or not any segregations or micro-clusters existed inside of ingots because segregations or macro-clusters could have a negative effect to cold work process. Fig. 1 shows the SEM-EDS images of AFS containing 5 wt.% Al and 7 wt.% Al, respectively. In case of AFS with 5 wt.% Al, any segregations or micro-clusters were not observed. However, in AFS containing 7 wt.%, segregations such as cracks were observed. Furthermore, those still remained after the homogenization heat treatment. Those did not affect hot-rolling process. However, those could be a factor of crack initiation and propagation in the cold working process.



(a) 5 wt.% Al



(b) 7 wt.% Al

Fig. 1. Results of line scanning method for (a) 5 wt.% and (b) 7 wt.% aluminum added

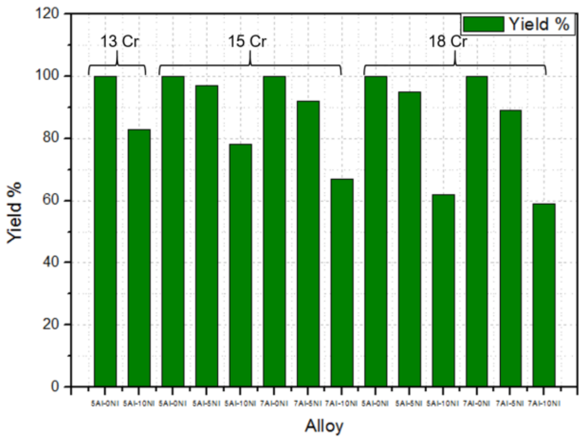
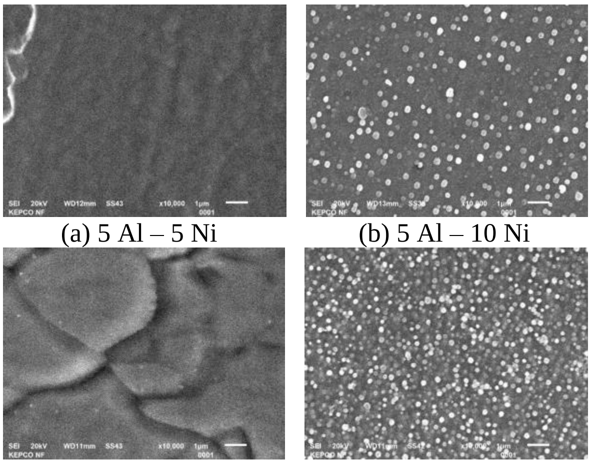



Fig. 2. Results of workability evaluation for AFS alloys.

Fig. 2 shows the results of workability evaluation after hot-rolling. The workability depended on alloying elements, the workability of AFS alloys was significant reduced with the presence of Ni. But, the workability was not affected by other alloying elements (chromium and aluminum). It is thought that the presence of B2(Ni-

Al) precipitates formed during the hot work process could be responsible for the reduction of workability as shown in Fig. 3. As amount of aluminum increase, the amount of B2 precipitates increased, and the nickel addition was increased the dissolution temperature of the B2 precipitates. In the case of alloys containing 10 wt.% nickel, B2 precipitates were observed during homogenization heat treatment. The workability in the hot rolling process was degraded by the B2 phase precipitates. Therefore, it was expected that the workability can be improved by controlling the proper amount of nickel and the processing temperature.



(a) 5 Al – 5 Ni (b) 5 Al – 10 Ni

(c) 7 Al – 5 Ni (d) 7 Al – 10 Ni

Fig. 3. The distribution of B2 precipitations observed after intermediate heat treatment in (a) 5 Al – 5 Ni, (b) 5 Al – 10 Ni, (c) 7Al – 5 Ni and (d) 7 Al – 10 Ni alloys

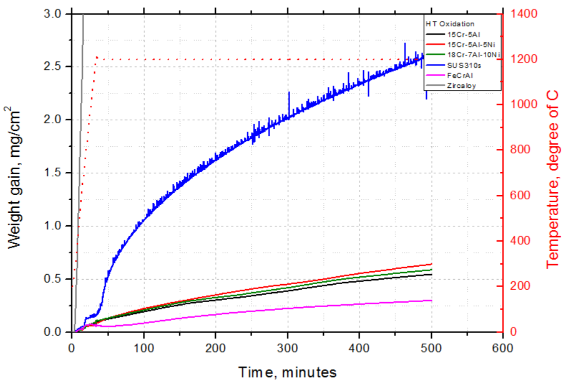



Fig. 4. Results of high temperature oxidation for Fe-based ferritic alloys

Fig. 4 shows the high temperature oxidation test results of AFS alloys with reference commercial alloys. The oxidation weight gain of tested AFS alloys was about 1/1000 compared to commercial zirconium alloy. And, AFS alloys showed good oxidation resistance compared to the Fe-based SUS310s alloy. Since the present state does not consider the minor alloying element such as yttrium, there is a possibility that the high temperature oxidation resistance is improved though optimization of alloying composition. In AFS alloys, there was no significant difference due to alloying elements such as aluminum, chromium and nickel. Based on these results, it was considered that there is no influence by the aluminum dissolution due to the forming B2 precipitates containing aluminum.

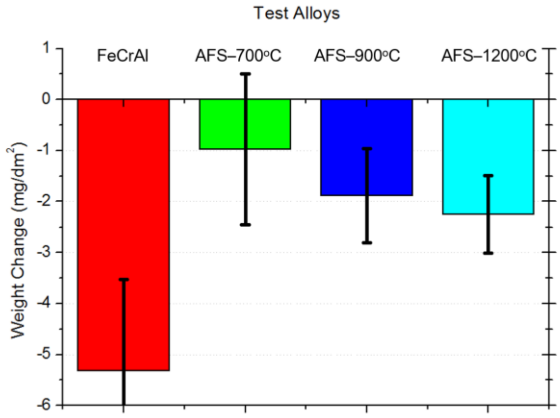



Fig. 5. Results of corrosion test for normal operation with addition of nickel and heat treatment temperature

Fig. 5 shows the results of the corrosion test in the simulated primary water environment for 44 days. As a results of comparison between FeCrAl alloy and alloy containing small amount of nickel, it was observed that the weight loss was significantly reduced with presence of nickel. Nickel may help to form a protective oxide film on metal surface such as nickel-chromite. And the trend of weight loss in the heat treatment conditions were insignificant.

## 4. Conclusions

In this study, the workability and the high temperature oxidation property of AFS alloys were evaluated. The amount of aluminum was controlled to ~ 5% since segregation of aluminum had bad influence on the workability, and composition of alloying elements and processing temperature were controlled to prevent the forming B2 phase precipitates during the manufacture process. The high temperature oxidation behavior of AFS alloys was evaluated to show good performance, and it will be improved though optimization of alloying composition. The effect of addition of nickel on the reduction of weight loss was confirmed in the normal operation corrosion, based on this, the effect of nickel will be studied for oxidation mechanism.

## 5. Acknowledgements

This research has been carried out as a part of the nuclear R&D program of the Korea institute of Energy Technology Evaluation and Planning funded by Ministry of Trade, Industry and Energy in Korea.

(No. 20171510101990)

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