Preliminary Fabrication of Fe-based Alloy Cladding for Nuclear Fuel

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1. Introduction

Zr-based alloy is the only material currently used as a cladding material in pressurized water reactor for many decades, because of their good mechanical properties, adequate corrosion resistance, and low neutron absorption cross section [1]. However, since the accident at Fukushima Daiichi NPP, most of the attention in nuclear field has been focused on developing enhanced accident tolerant fuel (ATF) cladding as a first line of defense. The enhanced ATF cladding can be defined as a cladding that can tolerate accident situations for a considerably longer time period while having a similar or better the fuel performance during normal operation. In addition, the enhanced ATF cladding should have lower reactivity of steam to reduce hydrogen gas generation and enhanced mechanical properties for geometric stability of fuel cladding [2-3].

Various concepts of enhanced ATF cladding have been developed by fuel vendors, national laboratories, and universities. Framatome and Westinghouse is developing two different types of cladding that are Cr-coated cladding and SiC cladding. General Electric and Oakridge National Laboratory (ORNL) cooperated to develop a Fe-based alloy cladding called IronClad (FeCrAl) [3-5]. Nippon Nuclear Fuel Development (NFD) also developed FeCrAl-ODS cladding [6-7].

Taking all the aspects of enhanced ATF cladding into consideration, KEPCO Nuclear Fuel (KNF) focused on Fe-based alloy as one of the convincing candidate materials for enhanced ATF cladding. The Fe-based alloy cladding has advantages of better corrosion resistance and excellent high temperature oxidation resistance compared to commercial Zr-based alloy cladding [2]. On the other hand, this alloy does not have good fabricability owing to its high strength. Considering neutron economy and utility's economic benefits, wall thickness of the Fe-based alloy cladding must be thinner than commercial claddings while maintaining an identical outer diameter of those. In this study, fabrication process of Fe-based alloy cladding was selected, and preliminary fabrication was conducted through the process. At last, KNF's present and future work on Fe-based alloy cladding were introduced.

2. Methods and Results

2.1 Fabrication Process Selection

In order to select appropriate fabrication process of Fe-based alloy cladding, papers issued by other organizations were reviewed. Two organizations, ORNL and NFD, designed, and fabricated Fe-based alloy cladding with different methods shown in Table 1. ORNL fabricated the cladding through conventional industrial process (casting, extrusion and drawing), on the other hand, NFD fabricated the cladding through mechanical alloying, extrusion and pilgering. Most important part for cladding fabrication is tube making process because it must be able to precisely control the surface and dimension of the final product. Cold/warm drawing was performed by ORNL to fabricate claddings, but uniformity of tube was not satisfied in current tube specification since the wall thickness (WT) was not uniform. NFD adopted 3-roll pilgering which provides a fast, economical way to achieve extreme reductions in diameter and wall thickness, and successfully fabricated a cladding with precise dimension [4-7].

Considering paper review, KNF selected a pilgering process as a thin wall cladding fabrication process.

Table I: Cladding fabrication process and results of ORNL and NFD [4-7]

Process	ORNL	NFD
Ingot	Casting (VIM + HIP)	Powder Metallurgy
Master Bar	Extrusion + Drilling	Extrusion + Drilling
Tube	Warm Drawing / Cold Drawing / Pilgering	Pilgering
Result	Failed / Partially succeeded / Under progress	Succeeded
Remarks	Ununiform WT / < 2 m length	Large Grain Size

2.2 Preliminary Fabrication

At first, chemical composition to fabricate a cladding was selected as Fe-24Cr-5.4Al. This chemical composition contains relatively high amount of alloying elements such as chromium and aluminum, which make iron alloys hard to work, compared to other commercial FeCrAl alloys. As well, it is similar to the chemical composition designed by KNF. Foreign manufacturers that have fabrication experience of FeCrAl alloy tube were selected for casting and pilgering. Next step to fabricate the Fe-based alloy cladding was a casting ingot.

Vacuum induction melting (VIM) and electro slag remelting (ESR) were performed to produce sound ingot. The ingot was forged and rolled to fabricate a master bar. This master bar was drilled and annealed. After that, reduction and annealing were performed several times by 3-roll pilger machine and bright annealing furnace to fabricate a cladding with 9.5 mm diameter and 0.35 mm thickness. Longest length of the cladding was 1,946 mm. Fig 1. Shows schematic diagram for cladding fabrication flow. The master bar and the cladding are shown Fig. 2.

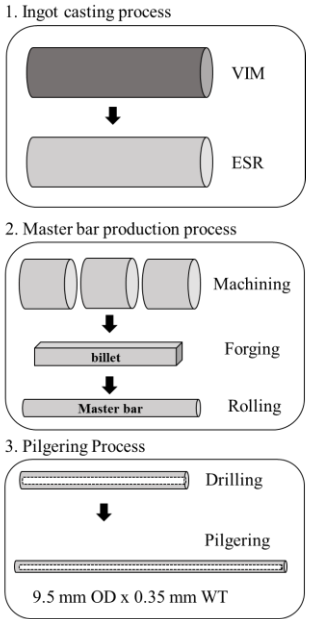
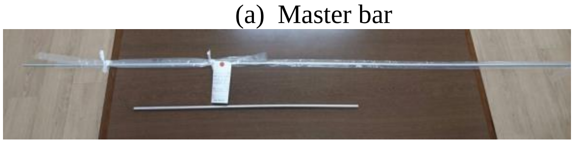


Fig. 1. Cladding fabrication process for thin wall tube.

(a) Master bar

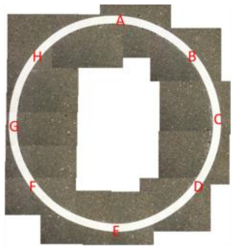


(b) Fe-based alloy Cladding

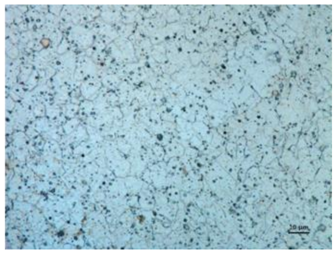
Fig. 2. Photographs of (a) Master bar and (b) fabricated Fe-based alloy Cladding.

2.3 Inspection

To verify dimensional uniformity of the cladding, outer dimension (OD) and wall thickness (WT) was measured by laser micrometer and optical microscope (OM). Fig. 3 (a) shows cross-sectional OM images of measuring WT. Average OD and WT were 9.520 +/- 0.003 mm and 0.351 +/- 0.002 mm. Average OD and tolerance were good enough to satisfy commercial cladding requirement. Finally a fine grain size was observed by OM as shown Fig 3 (b). The average grain size was less than 50 um that is relatively small size compared to the grain size of FeCrAl-ODS fabricated by NFD.



(a)



(b)

Fig. 3. OM images of the cladding (a) to measure wall thickness and (b) to observe microstructure (x 1000).

2.4 Present & Future Works

Through the successful experience of preliminary fabrication, Fe-based alloy ingot developed by KNF and Korea advanced institute of science and technology (KAIST) is under a pilgering process. The result of this fabrication will be available soon. KNF has another plan to produce various alloy ingots up to 500 kg at commercial process. The ingots will be forged and rolled to make master bar. The final product, thin wall cladding, will be fabricated by 3-roll pilger machine. The dimension of the target product will be 9.5 mm OD x 0.35 mm WT x 4000 mm L.

3. Conclusions

From the paper review, it was noticed that 3-roll pilgering process is one of the best way to fabricate a thin wall cladding.

Preliminary fabrication of Fe-based alloy cladding was conducted by foreign manufacturers. This process includes alloy casting, master bar production through forging and rolling, gun-drilling and pilgering. As a result of this attempt, Fe-based alloy cladding having precise dimension was fabricated very successfully.

From the fabrication experience, Fe-based alloy cladding developed by KNF and KAIST is fabricating, and KNF's project that produces ingots and claddings with large quantity at commercial process will be initiated soon.

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