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

# Microstructure and mechanical properties of Fe-base alloys as potential accident tolerant fuel cladding materials

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## 1. Introduction

Following the Fukushima accident in 2011, it was proposed that Zirconium alloy cladding in current commercial light water reactors (LWRs) was to be replaced with other accident tolerant fuel (ATF) materials including iron-chromium-aluminum (FeCrAl) cladding. Extensive testing and evaluation has been carried out to determine the suitability of Fe-base alloys under normal operation and simulated accident conditions [1,2] showing promising results. While other concerns for the Fe-base alloys currently being tested such as aging, irradiation and stress-corrosion cracking (SCC) behaviors, fabrication into a thin tube structure must be addressed for the practical implementation. Therefore, in this study, mechanical properties of developed Fe-base alloys were evaluated to check cold- and hot-workability in relation to the microstructure.

## 2. Materials and Experimental

Materials and processing conditions are described in which the compositions and microstructure of B51 are patented in KR 10-1833404 and KR 10-1779128, as well as PCT/KR2017/010276.

### *2.1. Materials*

Alumina-forming duplex stainless (ADSS, B51) alloy was designed as described in details [1] and prepared along with advanced ferritic steel (AFS, G12) alloy. Ingots of 42 kg were made by vacuum induction melting and homogenized at 1200 $^{o}$C while the compositions were analyzed by inductively coupled plasma atomic emission spectroscopy (ICP-AES) as present in **Table I**. The compositions of G12 alloy were provided in range for the patent pending protection.

Ingots were cut and hot-forged (HF) and/or hot-rolled (HR) into a plate or bar-shape between 800–1200 $^{o}$C while re-heated. Different post heat-treatments (PH) were applied at 700–1200 $^{o}$C for 1 h followed by air cooling. Here, the temperatures were set to engineer the fraction and distribution of phases.

Table I: Chemical compositions (ICP-AES)

| *Alloy* | *Fe* | *Ni* | *Cr* | *Al* | *Nb* | *Mn* | *Si* | *C* |
|---|---|---|---|---|---|---|---|---|
| *ADSS (B51)* | *Bal.* | *18.7* | *16.3* | *6.14* | *0.5* | *1.0* | *0.3* | *0.1* |
| *AFS (G12)* | | *<5* | *<18* | *<7* | *Minor elements controlled* | | | |

### *2.2. Experimental*

Microstructure characterization was performed by SEM in BSE mode (Fe-SEM; Hitachi SU8230). Vickers hardness test was carried out on the mounted specimens ground down to 4000 grit SiC paper with a load of 500 g with 10 s of dwell time. Also, plate-type mini-size tensile specimens with dimensions of 16-mm length (gauge width/length of 1.2/6 mm) and 0.5-mm thickness were tested parallel to the rolling direction at a crosshead speed of 0.1 mm/min.

## 3. Results and Discussion

### *3.1. Microstructure*

Representative SEM (BSE) images of B51R and G12 are shown in **Fig. 1**. Different processing conditions were applied to the alloys. For example, B51 was hot-forged (HF) at 1200 $^{o}$C and post-heat treated (PH) at 1000 $^{o}$C for 1 h. Depending on the compositions, B51 consisted of austenite, ferrite, and B2-NiAl phases and G12 had ferrite and B2-NiAl phases. Here, the intermetallic B2-NiAl phases were present in black color and circular shape (about 200–500 microns).

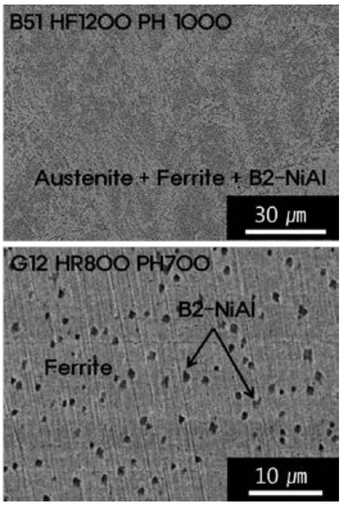

Fig. 1. SEM (BSE) images of B51 and G12 alloys.

### *3.2. Hardness and workability at high temperatures*

Micro-hardness values (HV0.5) were similar for both alloys, which B51 and G12 had HV0.5 of 352.2±19.1

and 358.0±10.5, respectively. The hardness values were very high as compared to other stainless steels while the larger standard deviation was resulted from the different phase regions (i.e. ferrite region showed higher values than austenite region.)

Despite the high strength, fabrication of bars and plates was successful for both alloys as shown in **Fig. 2**. The workability of both G12 and B51 alloys at high temperatures exceeded expectations where no side or surface cracks were observed in all forged bar and rolled plates. Here, the forging (cross-sectional ratio) and rolling (thickness %) reductions were about 16:1 and 80 %, respectively.

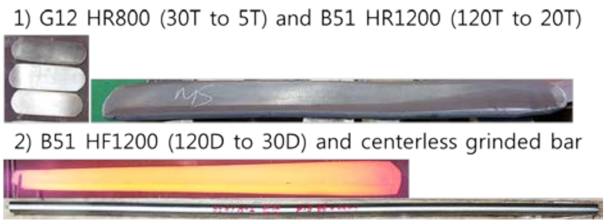

Fig. 2. Pictures of Fe-base alloys in as hot-forged bar and as hot-rolled plates.

### *3.3. Tensile properties and potential cold-workability*

B51 alloy exhibited a very high strength, with the yield strength and ultimate tensile strength being greater than 900 and 1100 MPa, respectively, which were higher than commercial high strength duplex stainless steels. Also, it was clear that B51 alloy had superior tensile properties over G12 alloy, it also had a higher tensile strength than ferritic FeCrAl alloys. In addition to the strength, the elongation of B51 was much higher than G12 which was comparable to Zircaloys (about 10 %), supporting the possibility of cold-working process such as pilgering for both alloys.

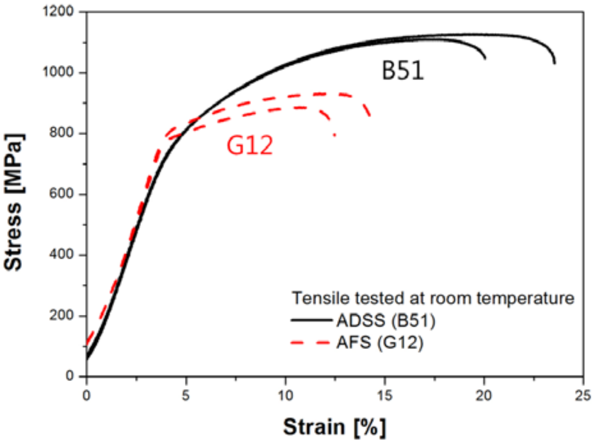

Fig. 3. Stress-strain curves from tensile tests at room temperature for B51 and G12 alloys.

## 4. Summary

Microstructure and mechanical properties of developed Fe-base alloys as potential ATF cladding materials were studied as the following results were obtained:

1) Depending on the compositions, austenite, ferrite, and B2-NiAl phases were present in different fraction and distribution.

2) Both B51 and G12 showed an excellent workability at high temperatures with similar Vickers micro-hardness values.

3) Tensile properties of B51 and G12 tested at room temperature showed very high strength as compared to commercial duplex and ferritic FeCrAl alloys, respectively. The uniform elongation of both alloys was comparable or better than Zircaloys showing potentials to be fabricated into a thin cladding by cold-working process.

## ACKNOWLEDGEMENT

This study was supported by the KUSTAR-KAIST international joint research project (N11180043) and MOTIE/KETEP project (No. 20171510101990) of the Republic of Korea. Financial support for three of the authors was provided by the BK-Plus program of the MSIP of the Republic of Korea.

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