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Boron-bearing Influences of 9Cr-0.5Mo-2W-V-Nb Ferritic/Martensitic Steels for a SFR Fuel Cladding

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1. Introduction

Currently the principal materials in a SFR (sodium-cooled fast reactor) of Gen-IV nuclear system are considering stainless steels (e.g. austenitic steels and ferritic/martensitic steels) for pressure boundary and structural applications in the primary circuit (cladding, duct, cold and hot leg piping, and pressure vessel). There are sound technical justifications for these material selections, and the adoption of these stainless steels for a wide range of nuclear and non-nuclear applications has generated much industrial technology and experience. However, there are strong incentives to develop advanced materials, especially cladding, for the Gen-IV SFR. The Gen-IV SFR is to have a considerable increase in safety and be economically competitive when compared with the conventional water reactors. To accomplish these objectives, the development of the fuel cladding material should be set forth as a premise because its integrity is directly related to those of the reactor system as well as the fuel in the Gen-IV SFR.

Since last year, a R&D program was launched to develop the improved ferritic/martensitic steel for the Gen-IV SFR fuel cladding. Categories of materials considered in the program included 8~12% Cr ferritic/ martensitic steels. A strong recommendation was made for the development of a high strength steel equivalent to or superior to ASTM Gr.92 steel to offset the difficulties encountered with commercial available steels of the 8~12% Cr group. That is, since fuel cladding in the Gen-IV SFR would operate under higher temperatures than 600°C, contacting with liquid sodium, and be irradiated by neutrons to as high as 200dpa, the cladding should thus sustain both superior irradiation and temperature stabilities during an operational life [1,2]. The newly developed advanced steel should overcome the severe drawback; mechanical properties, especially creep, are deteriorated at a higher temperature over 600°C [2,3]. In this study, as one of the composition modification, the influences of B-bearing 9Cr-0.5Mo-2W-V-Nb ferritic/ martensitic steels on the microstructural and mechanical properties were systematically investigated in order to evaluate the applicable validity as a cladding material for the Gen-IV SFR fuel.

2. Experimental

The three experimental ferritic/martensitic steels were mainly consisted of 9% Cr, 0.5% Mo, 2% W, and 0.4% V+Nb, and carbon and nitrogen were added into the steels in the range of 0.08~0.11%, 0.08~0.10%, respectively. In addition, the boron concentrations in the experimental steels were intentionally changed from 0 to 170 ppm so as to evaluate the influence of boron concentration in the steels (Table 1).

Table 1 Chemical composition of the experimental F/M steels

Exp. Steels	**Composition, wt.%**						
	Cr	**Mo**	**W**	**V+Nb**	**C**	**N**	**B**
B001	8.95	0.528	2.13	0.413	0.11	0.08	-
B002	9.02	0.524	1.96	0.403	0.08	0.10	0.008
B003	8.95	0.536	1.98	0.403	0.09	0.09	0.017

As mentioned in a previous study [4], the ingot of the each steel was 30 kg and prepared by using a vacuum induction melting (VIM). Plates of the steels were hot-rolled into 15mm in thickness after an annealing at 1150°C for 2 hours. The hot-rolled plates were normalized at 1050°C for 1 hour and then followed by a tempering at 750°C for 2 hours. After both of the normalizing and tempering heat-treatments, the samples were cooled to room temperature in air.

Optical microstructures of the steels were observed after the chemical etching with a solution of 93% H_2O, 5% HNO_3, and 2% HF in volume %. And the precipitate characteristics were analyzed with thin foil and carbon-replica specimens using by a TEM with EDS. In order to investigate the mechanical properties of the steels, Vickers micro-hardness tester, tensile tester, and creep tester were utilized for the specimen perpendicular to the rolling direction of the plate. The average hardness was taken from 10-measured values, which were obtained under a load of 500 g. The tensile tests were carried out by using specimens with a 25-mm-gage length in the temperature range from 25 to 700°C. The creep properties were evaluated after performing at 650°C with the stress conditions of 120, 130, and 140 MPa.

3. Results and Discussion

3.1. Optical & TEM Microstructures

From the optical microstructure observation, all experimental steels showed a typical tempered martensitic structure and it was impossible to distinguish among them. It was confirmed in a TEM observation that the steels revealed the tempered martensitic microstructure and the $M_{23}C_6$-type precipitates were distributed along the prior austenite grain boundaries. A small MX-type precipitates less than 100nm were also detected within the martensite lath in spite of the different composition in the steels. And the hcp M_2N-type precipitates were occasionally observed in the steels. This was thought that the nitrogen concentration in the steels be relatively higher than the conventional steels. Unfortunately, the boron-contained precipitates were not detected in our TEM study due to the small amount of the boron addition less than 200ppm. But the boron addition would affect the mechanical properties of the steels, which will be discussed in the following section.

3.2. Mechanical properties

Vickers hardness slightly decreased with an increase of the boron concentration in the experimental steels; the 170 ppm B-bearing steel was reduced by about 4% when compared with the non-boron containing steel. All of the experimental steels trended toward the decreasing strengths with a test temperature while the total elongations of the steels increased with the temperatures and showed a minimal value at the 400^{o}C. The tensile strengths of the boron-bearing in the steels were slightly with increasing the boron concentrations at 650^{o}C rather than 25^{o}C. But the total elongations of the boron-bearing steels decreased compared with the non-boron steels at 650^{o}C. From these results, the boron addition in the ferritic/martensitic steels would influence the hardness and tensile properties. That is, the hardness decreased but the tensile strength increased due to the boron addition in the steels. It was interpreted that the almost boron in the steel would be precipitated into the precipitates.

Creep tests were carried out under the applied stress conditions of 120, 130 and 140 MPa at 650^{o}C. The creep rate at the steady-state regime was reduced with an increase of the boron concentration in the steels but the rate was dependent on the applied stress. The sustain time without rupture during the creep testing under the 120MPa stress was also extended with the boron concentration in the steels and shortened with the applied stress (Fig. 1). The creep resistances of the experimental steels were analyzed from the creep rate and time-to-rupture. The creep properties in the steels were strongly relying on both of the boron concentration within the steels and the applied stress. The creep rupture elongation and reduction area were evaluated after the creep rupture. In the 120MPa creep test, the creep rupture elongation of the 170 ppm boron-bearing steels was the highest when compared with the other steels. The reduction of area after the creep rupture showed a decreasing trend with the boron concentration in the steels. From these test results, it was concluded that the 170 ppm boron-bearing steel could be one of promising candidate alloys for the fuel cladding in a SFR.

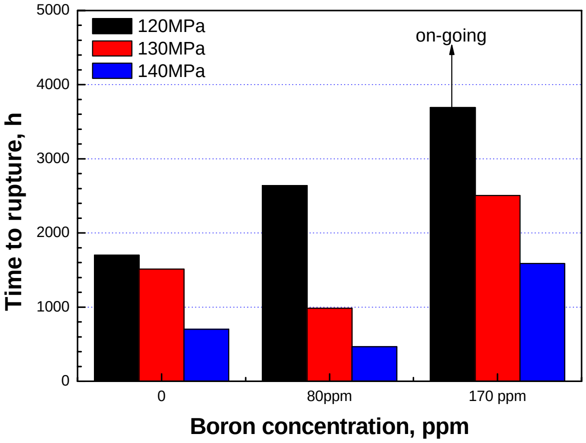

Fig. 1 Creep rupture time of the B-bearing steels at 650^{o}C

4. Conclusions

The 9Cr-0.5Mo-2W-V-Nb ferritic/martensitic steels are candidate materials as a SFR fuel cladding. From the viewpoint of microstructures, the boron-bearing steels revealed a typical tempered martensitic structure and showed the known precipitate type and distribution. The 170 ppm boron addition into the steel system improved the tensile strength and creep resistance at 650^{o}C, which was an operation temperature of the fuel cladding in the SFR.

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