Effects of Ta addition on the Microstructural and Mechanical Properties of 9Cr-0.5Mo-2W F/M Steels for a SFR Fuel Cladding

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1. Introduction

Today twenty fission reactors provide about 40% of the domestic electricity supply. The world-wide distribution of some nuclear reactors will be aging and will need replacement and enhancement to both keep pace with and to take up a large share of the growing world-wide electricity demand. A new generation (Gen IV) of nuclear plant concepts has become the focus of international advanced reactor activity. Gen IV nuclear systems embodies greater improvements and innovative advances in technology over earlier ones. The Gen IV systems are to have a considerable increase in safety and be economically competitive when compared with the existed commercial reactors. In particular, the systems should produce a significantly reduced volume of nuclear wastes. From this point of view, sodium-cooled Fast Reactor (SFR) is strongly considered as a future nuclear energy system in Korea.

Although higher operating temperatures are considerably required in order to improve the thermal efficiency of the SFR, the upper operating temperature would be limited to 550~600^oC for the conventional HT9 and mod. 9Cr-1Mo steels as a fuel cladding [1]. Since fuel cladding in the SFR would operate under a higher temperatures than 600^oC, 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]. A R&D program of advanced fuel cladding materials development for the SFR was recently launched in Korea.

Generally, the Ferritic/Martensitic steels (FMS) have been considered and designed as fuel cladding materials for the SFR because of their excellent heat-transfer coefficient and extra low irradiation swelling properties. However, the steels have a severe drawback; mechanical properties, especially creep, are deteriorated at a higher temperature over 600^oC [2,3]. A lot of studies were carried to overcome the problem of the F/M steels, including a composition modification and a microstructure control [4,5]. In this study, as one of the composition modification, the effects of Ta addition on the microstructural and mechanical properties of 9Cr-0.5Mo-2W F/M steels for the SFR Fuel cladding were investigated systematically.

2. Experimental

The five 9Cr-0.5Mo-2W F/M steels (B006~B010) used in this study were mainly consisted of 9% Cr, 0.5% Mo, 2% W, and 0.5% V+Nb+Ta and carbon and nitrogen were added into the steels in the range of 0.03~0.05% and 0.07~0.09%, respectively. The ingot of the each alloy was 30 kg and prepared by using an induction melting. Plates of the alloys were hot-rolled into 15mm in thickness after an annealing at 1150^oC for 2 hours. The hot-rolled plates were normalized at 1050^oC for 1 hour and then followed by a tempering at 750^oC for 2 hours. After both of the normalizing and tempering heat-treatments, the samples were cooled to room temperature in air.

Samples for the microstructural and mechanical evaluations of the steels were taken from the 15-mm-plates. 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 and tensile 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^oC, according to an ASTM standard procedure.

3. Results and Discussion

3.1. Microstructures

The optical microstructures of the steels revealed a typical tempered martensitic structure. But it was difficult to clarify the optical microstructural difference among the alloy composition. From the TEM observation, it could be observed that a reduction of the Nb concentration showed an increase of the lath width in martensitic structure when comparing the B009 and B010 alloys. Large precipitates (200~300 nm) were displayed at the prior austenite grain boundaries, which were identified as $M_{23}C_6$-type chromic carbides. Large NbC precipitates were also observed intermittently on the prior austenite grain boundaries. In addition, the $M_{23}C_6$-type precipitates were located on the lath boundaries of the martensitic structure. Nitride, carbide and carbonitride such as NbC, NbN, VN, Nb(CN) and (NbV)C were observed both at the lath grain boundaries and within the lath regime. These precipitates were MX-type precipitates and their sizes ranged from 10 to 40 nm. However, the M_2X-type precipitates could not be detected anywhere because higher tempering temperature and lower nitrogen concentration. In the case of the Ta-containing alloys (e.g. B009 and B010), Ta was mainly detected within the MX-type precipitates including Ta of 5~20 at.%. And the Ta concentration within the MX-type precipitates in the Ta-containing alloys increased with an increase of the Ta content as an alloying element.

3.2. Mechanical properties

Hardness tests were performed with a load of 500g at room temperature by using a Vickers micro-hardness tester. In our alloy system, the Vickers hardness increased with the concentration ratio of Ta to (Nb+V+Ta). The degree of hardness increase was also enhanced with an increase of the Ta concentration in the F/M steels. And it was found that an Nb addition was less effective than a Ta addition for a hardness increase of the F/M steels.

Tensile tests were carried out at temperature to 700^{o}C. YS and UTS were monotonously reduced with an increase of the test temperature up to 500^{o}C. But above that temperature, both strengths decreased rapidly. From the view point of an elongation change with a temperature variation, the minimal elongation was exhibited at 400^{o}C. As shown in Fig. 1, the YS and UTS increased slightly with an increase of the concentration ratio of Ta to (Nb+V+Ta). But the elongation was the lowest value at 0.2 of the ratio. These trends were shown in the tensile results tested at 650^{o}C. That is, both strengths were enhanced with the concentration ratio and the shortest elongation was shown at 0.2 of the ratio. And it could be said that the tensile strength increase at 25 and 650^{o}C was more effective for a 0.15% Ta addition than a 0.1% one. It was found from the tensile test results that the combination of 0.05% Nb + 0.15% Ta in our F/M steel system improved the tensile strength more than the 0.1% Nb + 0.1% Ta combination. It was concluded that that the Fe-9Cr-0.5Mo-2W-V-0.05Nb-0.15Ta steel could be one of promising candidate alloys for the fuel cladding in a SFR.

6. Conclusions

F/M steels are prospectively being considered as cladding materials of a SFR fuel. Ta addition to the F/M steel was more effective than the Nb one. And the hardness and tensile strength were enhanced with an increase of the concentration ratio of Ta to (Nb+V+Ta). But the resultant elongation was the lowest value at 0.2 of the ratio. From the relatively good properties of the 0.05% Nb+0.15% Ta combined alloy, the Fe-9Cr-0.5Mo-2W-V-0.05Nb-0.15Ta steel could be one of the promising candidate alloys for a SFR fuel cladding.

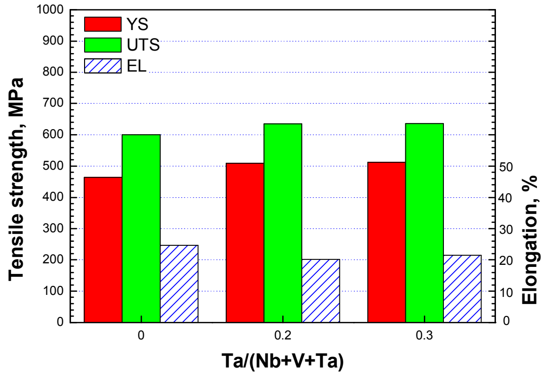

Fig. 1 Effects of the Ta addition on the tensile properties of the 9Cr-0.5Mo-1W F/M steels at R.T.

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