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Performance Evaluation of Advanced Ferritic/Martensitic Steels for a SFR Fuel Cladding

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1. Introduction

High-chromium(9-12 wt.%) ferritic/martensitic steels are currently being considered as candidate materials for cladding and duct applications in a Gen-IV SFR (sodium-cooled fast reactor) nuclear system because of their higher thermal conductivities and lower expansion coefficients as well as excellent irradiation resistance to void swelling when compared to austenite stainless steels [1,2]. Since the operation condition in the design of Gen-IV SFR would be envisioned to be harsh from the viewpoints of temperature ($\geq$600°C) and irradiation dose ($\geq$200 dpa) [3], the primary emphasis is on the fuel cladding materials, i.e. high-Cr ferritic/martensitic steels.

The ferritic/martensitic steels for the fuel cladding are commonly used in a 'normalized and tempered' condition. This heat treatment involves a solutionizing treatment (austenitizing) that produces austenite and dissolves the $M_{23}C_6$ carbides and MX carbonitrides, followed by an air cooling that transforms the austenite to martensite. Precipitation sequence during a long-term creep exposure is strongly influenced by the distribution of those in the as heat treated condition of the steels. Their creep strength has been improved by their martensitic lath structure, the precipitation strengthening effects of $M_{23}C_6$ carbides and MX carbonitrides and the solid solution strengthening effects of Mo and W in the matrix [4]. Especially, the precipitation strengthening effect of MX is important because its coarsening rate is small and a fine particle size is maintained for a long-term creep exposure [5]. Z-phase formation from MX-type precipitates has been proposed as a degradation mechanism for a long-term creep regime [6].

The ferritic/martensitic steels should need to improve their performance to be utilized in the high burn-up fuel cladding. For this purpose, KAERI has been developing advanced ferritic/martensitic steels since 2007. This study includes some performance evaluation results of the mechanical and microstructural properties of the alloys.

2. Experimental Procedure

The experimental steels were designed to improve the creep performance at 650°C on the basis of ASTM Gr.92 steel. The major elements were 9% Cr, 0.5% Mo, 2.0% W, 0.2% V, 0.2% Nb, and 0.05% Ta. The minor elements such as C, N, B, and P were also controlled in the specific ranges. And Zr and Pt were added to evaluate their effects in the steel system. The ingots of the steels were melted by a vacuum induction melting (VIM) method and hot-rolled to a 15mm thickness at 1150°C. After the hot-rolling, specimens were normalized at 1050°C for 1 hour and then they were tempered at 750°C for 2 hours. All the specimens were cooled in air at room temperature after the austenitization and tempering treatments. Tensile and creep tests were performed at 650°C.

Precipitates of the as-tempered samples were characterized by using TEM (transmission electron microscope) and OM (optical microscope). Extracted carbon replicas for TEM observation were prepared by the evaporation of carbon on a polished and etched sample surface followed by a dissolution of the metallic matrix in an etchant of 10% HCl and 90% methanol at a voltage of 20V at 25°C.

3. Results and Discussion

3.1 Tensile Properties

Tensile tests were carried out in the temperature range of room temperature to 700°C. The yield strength and ultimate tensile strength of the experimental steels decreased as an increase of test temperature while total elongation of the steels increased to about 20% at 700°C. The tensile strength of B007 at 650°C exhibited 347 MPa, which were much higher than that (290 MPa) of reference ASTM Gr.92 steel. Compared to the reference steel, the increase of the amounts of Nb and/or W as an alloying element improved the tensile strength of the steels. Furthermore, the combination of lower N and higher B could increase the tensile properties of the steels.

But the addition of phosphorus (50 ppm) could not affect the tensile properties. The additional Zr and Pt in the experiential steel system would enhance the tensile properties such as the yield strength and ultimate tensile strength. In the case of the addition of Ge and Cu, the tensile strength did not improve the tensile performance of the steels.

3.2 Creep Properties

Creep performance of the experimental steels was improved by the higher Nb content than the reference Gr. 92 steel. The optimal Ta content was ranged from 0.02 to 0.1 wt.% from the viewpoint of creep resistance.

The higher (3 wt.%) W-contained steel showed a better creep resistance when compared to the reference Gr.92 steel. The lower N (0.02wt.%) and/or higher B (150 ppm) contained steels the most excellent creep performance under the constant load conditions of140 and 150 MPa. And the V had affected a good creep properties between 0.1 and 0.2 wt.%. In the case of the Zr and Pt contained steels, the addition of the elements into the steel system was favor of the improvement of their creep resistance.

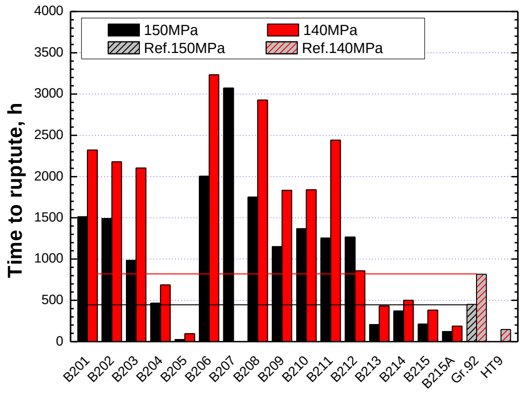

Fig. 1 Creep rupture of new F/M steels at 650^{o}C

3.3 Microstructural Properties

The experimental steels show a typical tempered martensitic microstructure after the normalizing and tempering treatments. The martensite lath width showed a tendency to decrease in the steels having the excellent tensile and creep properties. The $M_{23}C_6$ carbides were formed as major precipitates around the prior-austenite and lath boundaries. Small content of MX-type carbonitride precipitates (Nb-rich MX and V-rich MX) was observed on both boundaries and in their interiors. The Ta below 10 at.% was incorporated into the Nb-rich MX precipitates. Additionally, Laves phases as well as M_2X precipitates were occasionally detected on both boundaries in the higher W-contained steels. And it was thought that the combination of the lower N and higher B could improve its creep properties due to an inhibition of BN precipitation on both of the martensitic lath and the prior austenite grain boundaries.

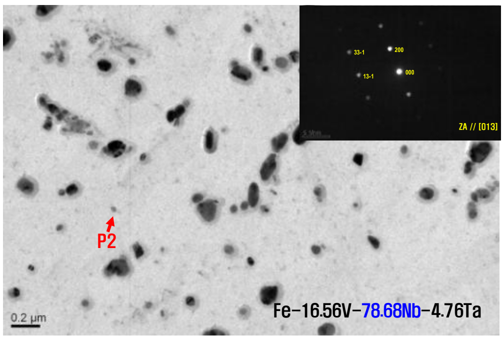

Fig. 2 Nb-rich MX precipitate with Ta in B207 steel

4. Conclusions

It was summarized that some of the experimental steels had a higher creep performance than the reference ASTM Gr.92 steel. It was thought that the higher Nb amount and additional Ta in the steels could enhance the creep rupture stress at 650^{o}C since the Nb-rich MX precipitates would stabilized by the incorporation within the precipitates. And the combination of the lower N and higher B could improve its creep properties due to an inhibition of BN precipitation on both of the martensitic lath and the prior austenite grain boundaries.

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