Assessment of 13~19%Cr Ferritic Oxide Dispersion Strengthened Steels for Fuel Cladding Applications

J.S. Lee[1)], I.S. Kim[2)], A. Kimura[3)], K.N. Choo[4)], B.G. Kim[4)], Y.S. Choo[4)], Y.H. Kang[4)]
1) Center for Advanced Reactor Research, KAIST 373-1, Daejon 305-701, South Korea, jslee2@kaist.ac.kr
2) Department of Nuclear and Quantum Engineering, KAIST 373-1, Daejon 305-701, South Korea, iskim@kaist.ac.kr
3) Institute of Advanced Energy, Kyoto University, Gokasho, Uji, Kyoto, Japan, kimura@iae.kyoto-u.ac.jp
4) Korea Atomic Energy Research Institute, P. O. Box 105, Daejeon 305-600, South Korea

1. Introduction

Oxide dispersion strengthened (ODS) steels considered as one of the promising candidate materials not only for fusion reactor blanket system, but for fuel clad materials of high burn-up operation of light water reactor (LWR) and supercritical pressurized water reactor (SCPWR). For the realization of fuel clad in LWR and SCPWR, the requirements of performance are high resistance to irradiation embrittlement, corrosion resistance and low susceptibility to hydrogen induced cracking. It was reported that in high strength martensitic steels several wppm of hydrogen could induce considerable reduction in ductility accompanied by a change in the fracture mode from microvoid coalescence type ductile fracture to intergrannular or cleavage type brittle fracture [1]. In addition, as the ferritic ODS steels have an inherently ductile to brittle transition behavior, the assessment of ductile to brittle transition temperature (DBTT) is very important for reactor safety in case of emergency core cooling accident.

In this work, the effects of hydrogen on the tensile properties of ODS steels are investigated to evaluate the susceptibility to hydrogen embrittlement of the ODS steels, and ductile to brittle transition behavior is also determined by small punch (SP) test.

2. Experimental

The materials used in the present research were three kinds of ODS steels and a 9Cr-2W reduced activation martensitic steel (RMS). The ODS steels are indexed as K1, K2 and K4. The ODS steels were produced with changing chromium and aluminum contents by keeping yittria (Y_2O_3) contents of 0.36~0.38 wt. %. Small size tensile specimens (gage length = 5 mm, $1.2^w \times 0.25^t$ mm) and disk type SP specimens ($3\varphi \times 0.28^t$ mm) were sampled from the extruded rod so that the axis direction is parallel to longitudinal (L) or transverse (T)-direction with respect to the extruded direction. Cathodic hydrogen charging was carried out at room temperature for 30 min and continued during tensile testing in a solution of 1N H_2SO_4 with an addition of 10 mg/l of As_2O_3. For hydrogen charging three electrodes system was used and constant current density, I_a, was imposed on the specimen in the range from 100 to -520 A/m^2. Tensile tests were carried out at a strain rate of 9×10^{-5} s^{-1} at room temperature. SP test was performed at a cross-head speed of 0.2 mm/min. at temperatures from 303 to 77 K.

3. Results

3.1. Ttransition of fracture strain by H charging

The changes in plastic fracture strain (ε_{pf}) of ODS steels and a 9Cr-2W RMS as a function of the square root of applied current density are summarized in Figure 1. In the L-direction, the ε_{pf} of ODS steels was about 0.14 in air, and an abrupt reduction occurred with increasing current density. The transition behavior of K2-L and K4-L is very similar. The critical current density where the ε_{pf} becomes 50 percent of that in air was approximately -42.5 and -23.0 A/m^2, respectively. In the T-direction, the fracture strain of K1-T, K2-T and K4-T ODS steels was about 0.10, 0.097 and 0.03 in air, respectively, but resulted in zero plasticity after applying a small amount of cathodic current. The critical current density was 0 A/m^2, irrespective of the materials.

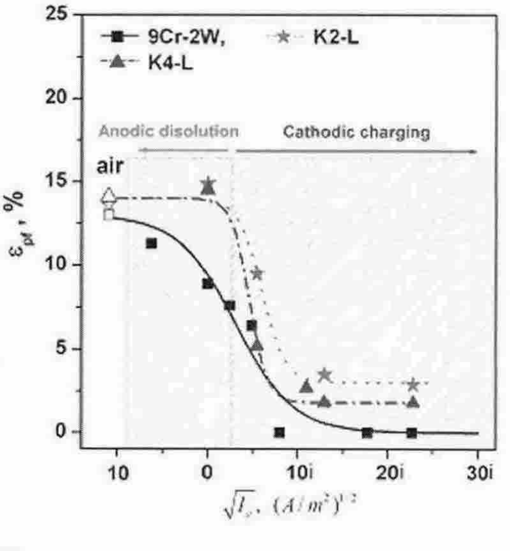

Figure 1. The dependence of plastic fracture strain (ε_{pf}) on the hydrogen charging current density in L-direction.

3.2. Critical hydrogen concentration for brittle fracture

As shown in Figure 2, the ODS steels contained a higher concentration of hydrogen than 9Cr-2W RMS at the same cathodic charging condition, and the critical hydrogen concentration required to induce intergranular cracking in ODS steels and 9Cr-2W RMS is in the range of 10-12 and 1-2 wppm, respectively.

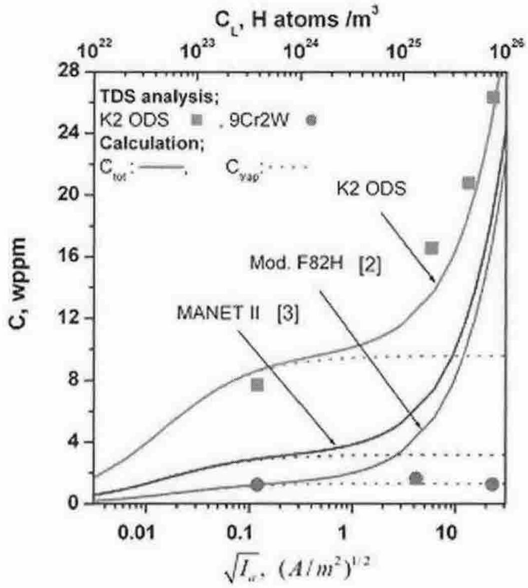

Figure 2. Experimental and calculated hydrogen contents in K2 ODS and martensitic steels as a function of current density. The calculation used the trap densities (N_t) and binding energy (E_b) of 6.3×10^{24} sites/m^3 and 39.0 kJ/mol for Mod. F82H and 1.5×10^{25} sites/m^3 and 39.5 kJ/mol for MANET II, respectively [2, 3].

3.3. SP ductile to brittle transition behavior

The changes in SP energy in each ODS steel are summarized in Figure 3, showing a typical ductile to brittle transition behavior depending on the test temperature.

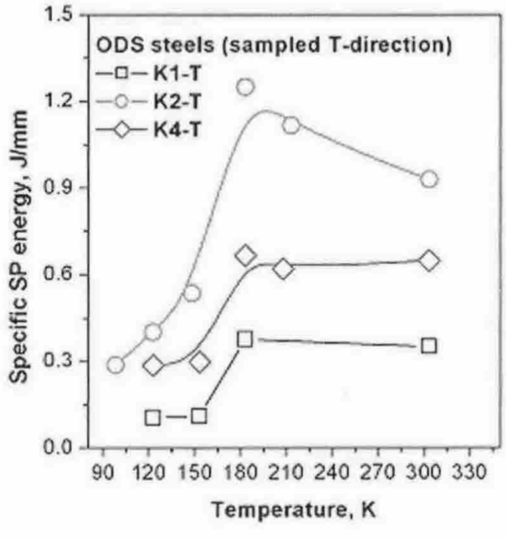

Figure 3. The changes in specific SP energy of ODS steels as a function of test temperature in T-direction.

In K2 T ODS steel, it showed an increase in SP energy with decreasing test temperature up to 183 K, and abrupt drop of SP energy was observed by further cooling. However, the increase in SP energy was not detected in K1-T and K4-T ODS steels up to the temperature of 183 K, and showing lower-shelf SP energy from 153 to 77 K. As expected from the tensile properties, K1-T ODS steel revealed the lowest SP energy at all temperatures, and the SP-DBTT was about 170 K, irrespective of the ODS materials. Further, the ductile to brittle transition behavior was strongly dependent on the specimen sampling direction, namely, L- or T- direction, and generally L-direction showed a lower SP-DBTT than that of T-direction.

4. Summary

1. Cathodic hydrogen charging considerably reduced the tensile ductility of ODS steels and a 9Cr-2W RMS. The hydrogen embrittlement of ODS steels was strongly affected by specimen sampling orientation, showing significant embrittlement in the T-direction. This comes from the microstructural anisotropy caused by elongated grains of ODS steels in L-direction.

2. The ODS steels contained a higher concentration of hydrogen than 9Cr-2W RMS at the same cathodic charging condition, and the critical hydrogen concentration required to transition from ductile to brittle fracture was in the range of 10~12 wppm, which approximately 10 times larger than that of a 9Cr-2W martensitic steel.

3. The ODS steels showed a typical ductile to brittle transition behavior and it strongly depended on the specimen sampling direction, namely L- and T-direction. In T-direction, the SP-DBTT was about 170 K, irrespective of the ODS materials, and L-direction showed a lower SP-DBTT than that of T-direction.

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