Available online at www.sciencedirect.com
ScienceDirect
Journal of Nuclear Materials 367–370 (2007) 1185–1189
journal of nuclear materials
www.elsevier.com/locate/jnucmat

Corrosion and stress corrosion cracking of ferritic/martensitic steel in super critical pressurized water

T. Hirose *, K. Shiba, M. Enoeda, M. Akiba

Naka Fusion Research Institute, JAEA, 801-1 Mukouyama, Naka, Ibaraki 311-0193, Japan

Abstract

A water-cooled solid breeder (WCSB) blanket cooled by high temperature SCPW (super critical pressurized water) is a practical option of DEMO reactor. Therefore, it is necessary to check the compatibility of the steel with SCPW. In this work, reduced activation ferritic/martensitic steel, F82H has been tested through slow strain rate tests (SSRT) in 23.5 MPa SCPW. And weight change behavior was measured up to 1000 h. F82H did not demonstrated stress corrosion cracking and its weight simply increased with surface oxidation. The weight change of F82H was almost same as commercial 9%-Cr steels. According to a cross-sectional analysis and weight change behavior, corrosion rate of F82H in the 823 K SCPW is estimated to be 0.04 mm/yr.

1. Introduction

The Japanese primary blanket option for a fusion DEMO reactor is the water-cooled solid breeder (WCSB) blanket with a reduced activation ferritic/martensitic steel, F82H as the structural material [1]. A water-cooled blanket is the nearest concept to practical use because conventional power plant technologies could be applicable. In some thermal power plants, super critical pressurized water (SCPW) has been used because of its higher thermal efficiency and a simpler plant concept. In recent fusion demonstration reactor concepts, SCPW with inlet/outlet temperatures of 553/783 K and coolant pressure of 25 MPa was selected for the demonstration reactor, to achieve a thermal efficiency of 41% [2]. In the blanket module, the structural material is required to be as thin as possible because of a requirement of efficient tritium breeding. The wall thickness of the cooling tube in the recent blanket design was less than 2 mm. It is required to be the boundary of SCPW and beryllium neutron multiplier because a reaction between them drastically increases inner pressure of the module [3]. Therefore, the corrosion resistance in SCPW is one of the most important requirements for fusion structural materials. The objective of this work is to evaluate the corrosion performance of F82H in a SCPW environment, including stress corrosion cracking (SCC) susceptibility and weight change behavior.

2. Experimental

The material used was Japanese RAF/Ms, F82H 5000 kg heat produced in 1997. The mechanical

* Corresponding author. Tel.: +81 29 270 7516; fax: +81 29 270 7489.
E-mail address: hirose.takanori@jaea.go.jp (T. Hirose).

0022-3115/$ - see front matter © 2007 Published by Elsevier B.V.
doi:10.1016/j.jnucmat.2007.03.212

properties of this heat are almost the same as the heat for IEA round-robin tests [4]. The details of this heat are presented elsewhere [5,6]. The chemical composition of F82H steel plate in wt% is Fe–0.095C–0.1Si–0.1Mn–<0.005P–0.003S–7.72Cr–1.95W–0.18V–0.04Ta–<0.02Ni–<0.01Mo–0.005Ti–0.00016B–0.01N–0.0001Nb. The plate was 32 mm thick and heat-treated as follows: 1313 K/0.5 h/air cooled (normalizing) and 1023 K/1.5 h/air cooled (tempering). A round bar specimen, which had a gauge section of 4 mm diameter by 20 mm was used for slow strain rate testing (SSRT) with its longitudinal direction parallel to the rolling direction. Coupon specimens (6 mm × 20 mm × 20 mm) were used for weight measurement. The specimen surface was mechanically polished to 0.1 μm in average roughness, Ra.

The SSRT was performed in an autoclave with a strain rate of $3.3 \times 10^{-7}\ s^{-1}$. The dissolved oxygen (DO) concentration of the water was controlled at 0.2 wt ppm at the inlet of the autoclave by injections of dry air and nitrogen gas to the conditioning tank as measured with a dissolved oxygen sensor. The electric conductivity was below 0.08 μS/cm at inlet and below 0.4 μS/cm at outlet of the autoclave. The autoclave volume was 783 mm^3 and the flow rate of SCPW was $5.6 \times 10^{-7}\ m^3\ s^{-1}$. Therefore, flow effects were negligible in this system. The tests were conducted at 563–823 K in the high purity water at 23.5 MPa. The water temperature was measured and controlled by thermocouples in Inconell#625 sleeve located in the autoclave. After the test, the fracture surfaces and oxidation products thereon were examined by scanning electron microscopy with energy dispersive X-ray spectrometry (SEM-EDX) and weight change was measured by a micro-balance.

3. Results and discussion

3.1. SCC susceptibility

Fig. 1 shows the test temperature dependence of tensile strength and ductility under SSRT conditions as well as tensile data in vacuum. With SSRT, 0.2% proof stress ($\sigma_{0.2}$) and ultimate tensile stress (σ_U) significantly decreased with increasing test temperature. Total elongation (ε_T) and reduction of area (RA) of SSRT were comparable to those of tensile tests in vacuum. The reduction of strength was significant at temperatures higher than 750 K. Because the strain rate of $3.3 \times 10^{-7}\ s^{-1}$ was sufficiently slow to allow creep deformation, the reduction of strength could be associated with this mechanism [7].

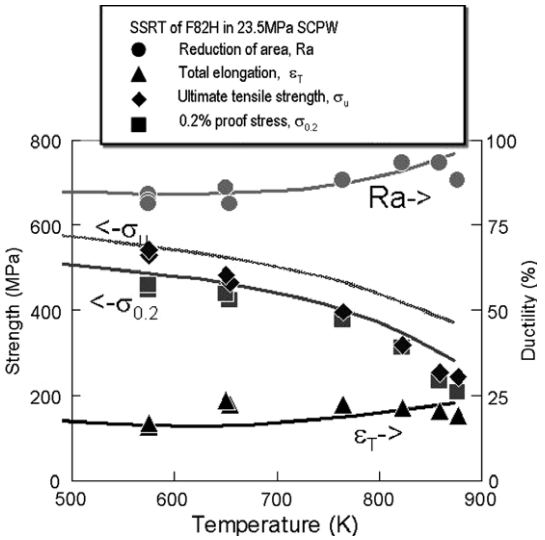

Fig. 1. Temperature dependence of strength and ductility under SSRT conditions. Solid lines represent tensile data in vacuum.

Typical stress–strain curves of SSRT tests are presented in Fig. 2 together with the curves of tensile tests under vacuum. Although the SSRT curves showed slight stress fluctuation, a qualification test without the specimen revealed that the fluctuation was caused by friction between the pull-rod and seal. Serration was not observed on stress–strain curves of any specimens. SEM micrographs of fracture surface and side surface are presented in Fig. 3. All of the specimens demonstrated ductile dimple fracture with corrosion products. Observa-

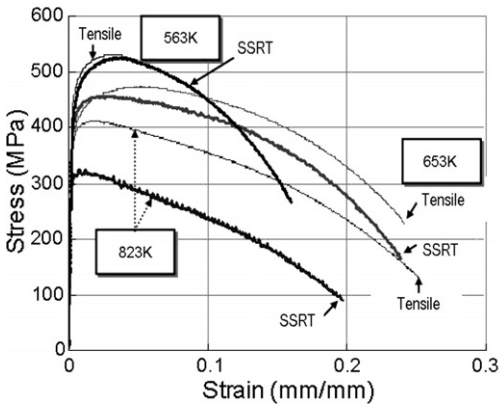

Fig. 2. Stress–strain relationship in SSRT.

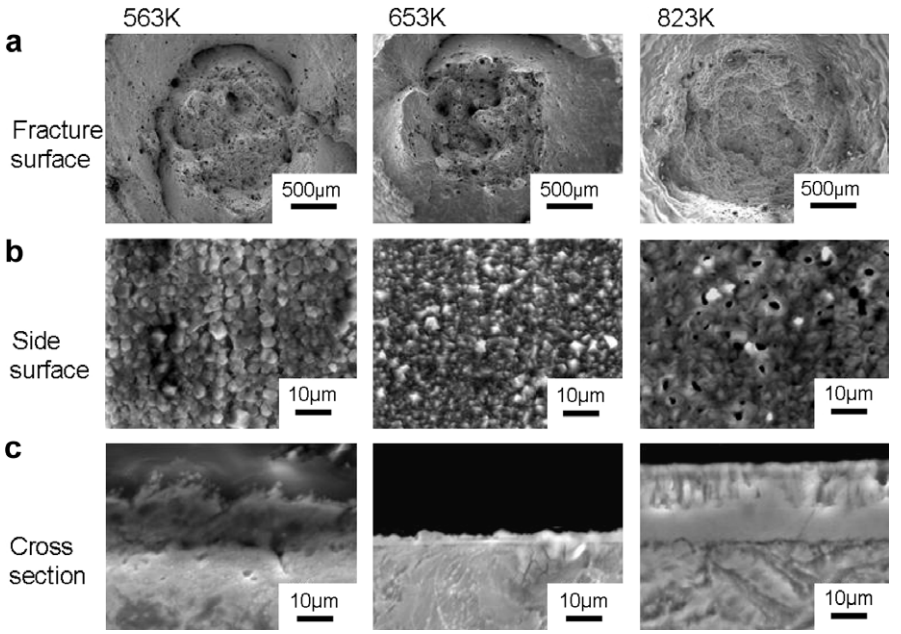

Fig. 3. SEM micrographs of SSRT tested F82H.

tions on the side surface and cross-section revealed complete coverage by blocky corrosion products and their facet size increased with the test temperature. There was neither cracking nor exfoliation on the corrosion products. The result of elemental analysis on the cross-section of the specimen tested at 823 K is presented in Fig. 4. The SSRT sample shows a duplex oxide structure, in which the scale consists of an outer blocky oxide and an inner dense oxide. The elemental mapping images revealed the outer block was iron oxide and the inner dense layer was chromium rich oxide. In the chromium image, bright contrast, which represented chromium carbides at grain boundaries, was observed in the base

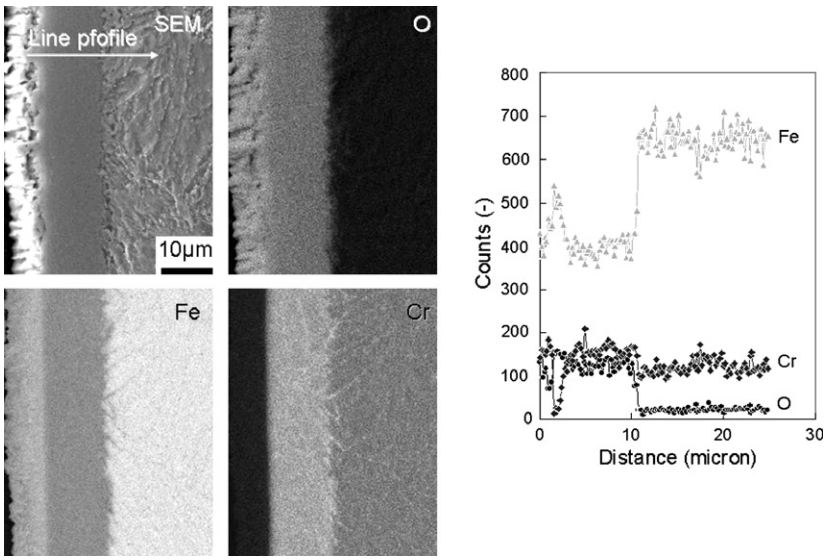

Fig. 4. Cross-sectional morphology and elemental analysis on F82H tested at 823 K SCPW.

metal and chromium rich oxide layer besides the base metal. Therefore, the original surface of F82H was the boundary between iron-rich layer and chromium rich layer. According to these results, the chromium layer was formed by iron transfer to the SPCW/base metal boundary. Therefore, the thickness reduction of F82H in the SCPW should be estimated by the thickness of the chromium rich (iron-poor) layer.

3.2. Weight change

The weight changes as a function of test duration for F82H in SCPW are presented in Fig. 5 and the surface morphologies of corrosion products are shown in Fig. 6. The weight gain increased with test temperature and is consistent with the grain size of corrosion product. The surface demonstrated neither cracking nor exfoliation. Therefore, the weight gain is considered to be simply caused by growth of iron-rich oxide on the surface. The time dependence of weight change has been described through the plot of parabolic curves. The weight gain of F82H was 5–6 times larger than that of SUS316 and was almost the same as commercial 9%-Cr steel such as T91 and NF616 [8,9]. There was no significant difference between 8%-Cr and 9%-Cr. According to the relationship between the thickness of chromium rich oxide layer (Figs. 3 and 4) and the weight gain behavior (Fig. 5), the corrosion rate of F82H in 823 K SCPW is estimated to be 0.04 mm/yr [9].

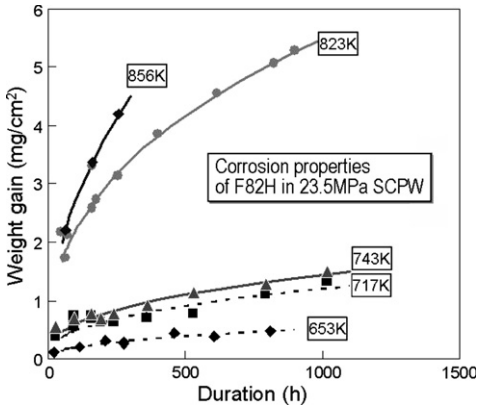

Fig. 5. Weight change as a function of test duration for F82H in SCPW.

4. Summary

Stress corrosion cracking susceptibility and corrosion behavior of F82H was tested at 560–820 K in 23.5 MPa SCPW. F82H did not demonstrate stress corrosion cracking susceptibility in the SCPW. Adherent oxide was formed on the F82H in the SCPW and there was no cracks and exfoliation up to 1000 h. The weight change in SCPW was caused by high temperature oxidation and its time dependence has been described through the plot of parabolic curves. The weight change of F82H (8%-Cr steel) was almost same as commercial 9%-Cr steels. The thickness reduction of F82H must be estimated by the thickness of the chromium rich (iron-poor) oxide layer. The corrosion rate of F82H in SCPW is estimated to be 0.04 mm/yr.

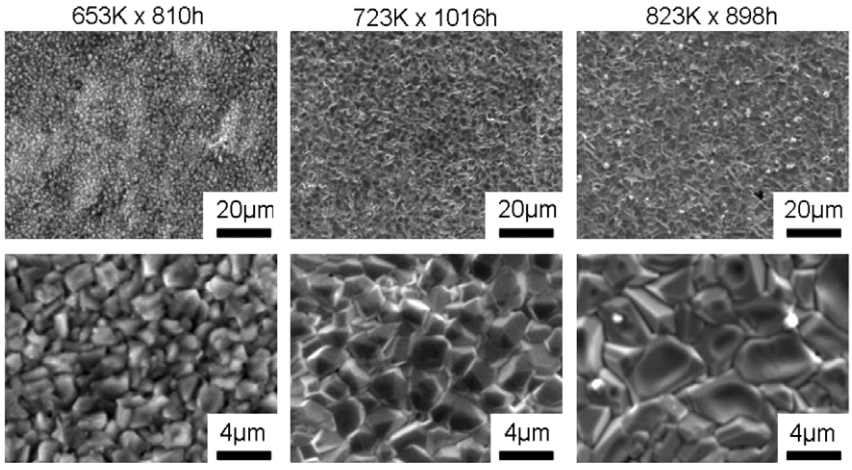

Fig. 6. Surface morphologies of F82H after exposure to SCPW.

References

[1] K. Shiba, M. Enoeda, S. Jitsukawa, J. Nucl. Mater. 329–333 (2004) 243.
[2] S. Nishio, J. Ohmori, T. Kuroda, K. Tobita, M. Enoeda, D. Tsuru, T. Hirose, S. Sato, Y. Kawamura, H. Nakamura, M. Sato, and The DEMO Plant Design Team, Fus. Eng. Des. 81 (2006) 1257.
[3] Y. Nomoto, S. Suzuki, K. Ezato, T. Hirose, D. Tsuru, H. Tanigawa, T. Hatano, M. Enoeda, M. Akiba, Fus. Eng. Des. 81 (2006) 719.
[4] M. Oda, T. Kurasawa, T. Kuroda, T. Hatano, H. Takatsu, JAERI-Tech 97-013, 1997.
[5] T. Hirose, K. Shiba, T. Sawai, S. Jitsukawa, M. Akiba, J. Nucl. Mater. 329–333 (2004) 324.
[6] T. Hirose, K. Shiba, M. Ando, M. Enoeda, M. Akiba, Fus. Eng. Des. 81 (2006) 645.
[7] K. Shiba, T. Nakata, Y. Kohno, M. Ando, H. Tanigawa, J. Nucl. Mater., these Proceedings.
[8] M. Harada, O. Kubota, H. Anabuki, Kobe Steel Engineering Reports, vol. 53, No. 3, 2003, p. 92.
[9] Y. Chen, K. Sridharan, Todd Allen. in: Proceedings of the NACE-Corrosion Annual Conference, Houston, TX, No. 5391, April 2005.