Effects of Hydrogen Peroxide on Intergranular Stress Corrosion Cracking of Stainless Steel in High Temperature Water, (V)

Characterization of Oxide Film on Stainless Steel by Multilateral Surface Analyses

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The difference in electrochemical corrosion potential of stainless steel exposed to high temperature pure water containing hydrogen peroxide (H2O2) and oxygen (O2) is caused by differences in chemical form of oxide films. In order to identify differences in oxide film structures on stainless steel after exposure to H2O2 and O2 environments, characteristics of the oxide films have been examined by multilateral surface analyses, e.g., X-ray diffraction (XRD), Rutherford back scattering spectroscopy (RBS), secondary ion mass spectroscopy (SIMS) and X-ray photoelectron spectroscopy (XPS). Preliminary characterization results of oxide films confirmed that the oxide film formed under the H2O2 environment consists mainly of hematite (α-Fe2O3), while that under the O2 environment consists of magnetite (Fe3O4). Furthermore oxidation at the very surface of the film is much more enhanced under the H2O2 environment than that under the O2 environment. It was speculated that metal hydroxide plays an important role in oxidation of stainless steel in the presence of H2O2. The difference in electric resistance of oxide film causes the difference in anodic polarization properties. It is recommended that several anodic polarization curves for specimens with differently oxidized films should be prepared to calculate ECP based on the Evans diagram.

KEYWORDS: BWR type reactors, hydrogen peroxide, oxide film, stainless steels, surface characterization, hematite, magnetite, electrochemical corrosion, intergranular corrosion, clacking

I. Introduction

Hydrogen water chemistry (HWC) has been applied to moderate corrosive circumstances in the primary cooling systems of boiling water reactors (BWRs). The HWC effects are influenced not only by the amount of hydrogen injected into the feed water but also reactor types, e.g., BWR-2 through -6, core size, shroud diameter, downcomer width, presence or absence of jet pumps and plant operational conditions, e.g., power density and distribution, recirculation flow rate, dose rate and flow velocity at the downcomer region, and jet pump efficiency. Oxygen and hydrogen peroxide concentrations change along the recirculation flow path so that corrosive circumstances differ between locations in the primary cooling systems.

Several indexes for corrosive circumstances have been proposed to evaluate the effects of HWC in BWR plants. One of the most common indexes of corrosive circumstances is electrochemical corrosion potential (ECP). Electrochemical corrosion potential is determined by a combination of surface conditions of a specimen and concentrations of oxidants, e.g., oxygen, hydrogen peroxide and other corrosive radiolytic species. Unfortunately, most data concerning the effects of ECP on intergranular stress corrosion cracking (IGSCC) have been obtained by changing oxygen concentration. There are only limited data concerning the relationship between hydrogen peroxide concentration, ECP, and generation and propagation of IGSCC. One of the reasons why fewer experimental data dealing with hydrogen peroxide have been reported is the difficulty of making experimental measurements because of hydrogen peroxide decomposition at elevated temperatures.

Decomposition of hydrogen peroxide is divided into two processes: (1) bulk decomposition (thermal decomposition in the bulk water), and (2) surface decomposition (decomposition by contact with metal surfaces). In the case of the reactor water, the extent of surface decomposition is a hundred times more than that of bulk decomposition. In order to establish conditions with less temperature fluctuation and less concentration depression at the point of interest, the authors have tried using a polytetrafluoroethylene (PTFE) liner to get less surface decomposition and they fabricated an experimental apparatus consisting of an autoclave with the PTFE inner liner and connecting branch lines with PTFE inner liner for hydrogen peroxide injection at the autoclave inlet and sampling at the autoclave outlet.

Measured electrochemical corrosion potential (ECP) of type 304 stainless steel obtained in a high temperature, high pressure water loop showed hydrogen peroxide (H2O2) resulted in a much higher ECP than oxygen (O2) with the same oxidant concentration. The crack propagation rate of intergranular stress corrosion cracking (IGSCC) of stainless
steel was moderated by the decreased ECP in the H$_2$O$_2$ environment as well as in the O$_2$ environment. However, when the concentration of H$_2$O$_2$ was lower than that of O$_2$ but the ECP remained the same, it was observed that the crack propagation rate in the H$_2$O$_2$ environment tended to be lower than that in the O$_2$ environment.\(^\text{13}\)

Results of X-ray diffraction measurements of oxide films on stainless steel specimens exposed to H$_2$O$_2$ and O$_2$ environments showed that the difference in the ECP was mainly due to the chemical form of the oxide film on the stainless steel specimens.\(^\text{14}\) Hematite ($\alpha$-Fe$_2$O$_3$) was observed for the specimens exposed to H$_2$O$_2$ environment, while magnetite (Fe$_3$O$_4$) was the main oxide species when exposed to the O$_2$ environment.\(^\text{14}\)

In order to confirm the difference in chemical form of the oxide films on the test specimens exposed to H$_2$O$_2$ and O$_2$ and to reveal the mechanism of oxide film formation, multi-analytical instrumentations were applied to examine the oxide film characteristics from a variety of viewpoints.

II. Experimental

1. Major Features of High Temperature, High Pressure Water Loop

The main features of the experimental apparatus are shown in Fig. 1.\(^\text{11–14}\) The water, which was deaerated in the make-up water tank and had its O$_2$ concentration controlled at the target level in the feed water tank, was fed to the autoclave through the regenerating heat exchanger and the main heater. The effluent water was polished by an ion exchange resin column to remove impurities and then fed back to the make-up water tank, where it was deaerated to remove oxygen and prevent its accumulation from decomposition of H$_2$O$_2$.

The autoclave and hydrogen peroxide injection line and sampling line were lined with PTFE to prevent surface decomposition of H$_2$O$_2$. The work electrodes were installed in the autoclave to measure ECP while changing hydrogen peroxide concentration ([H$_2$O$_2$]) at the autoclave inlet.\(^\text{11,13}\) In order to quantify the corrosive environment, [H$_2$O$_2$] was measured in the sampling line located at the autoclave outlet, and ECP was also measured at several locations in the autoclave (bottom and top) (Fig. 1). Major parameters for the experimental loop are shown in Table 1. Observed ECPs for both specimens under the exposure conditions shown in Table 1 were the same, 0 mV-SHE.

2. Test Specimens

Test specimens exposed to the H$_2$O$_2$ environment (diameter: 20 mm, height: 20 mm, thickness: 1 mm) were cut from a cylinder-shaped upper SUS electrode for ECP measurement (Fig. 2(a)), while those exposed to the O$_2$ environment (width: 10 mm, height: 20 mm, thickness: 1 mm) were flat sheets, which were originally placed just above the upper SUS electrode in the loop for the purpose of surface characterization of the oxide film (Fig. 2(b)). The test specimens exposed to H$_2$O$_2$ were cut into four pieces to allow examination of their inner surface (Fig. 2(c)). As any differences in test specimen shape might cause some undesirable effects on precise

![Schematic diagram of high temperature, high pressure loop](image)

### Table 1

<table>
<thead>
<tr>
<th>Item</th>
<th>Parameter</th>
<th>Parameter range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Autoclave</td>
<td>Temperature</td>
<td>561 K</td>
</tr>
<tr>
<td></td>
<td>Pressure</td>
<td>6.9 MPa</td>
</tr>
<tr>
<td></td>
<td>Flow rate</td>
<td>1–5 m$^3$s$^{-1}$</td>
</tr>
<tr>
<td></td>
<td>Flow velocity</td>
<td>1–2 cm$\cdot$s$^{-1}$</td>
</tr>
<tr>
<td></td>
<td>Conductivity</td>
<td>&lt;0.2 $\mu$S/cm</td>
</tr>
<tr>
<td></td>
<td>[O$_2$]</td>
<td>0–8,000 ppb</td>
</tr>
<tr>
<td></td>
<td>[H$_2$O$_2$]</td>
<td>0–1,000 ppb</td>
</tr>
<tr>
<td>Feed water tank</td>
<td>Temperature</td>
<td>280–300 K</td>
</tr>
<tr>
<td></td>
<td>Pressure</td>
<td>0.1 MPa</td>
</tr>
<tr>
<td></td>
<td>Conductivity</td>
<td>&lt;0.2 $\mu$S/cm</td>
</tr>
<tr>
<td></td>
<td>[O$_2$]</td>
<td>0–8,000 ppb</td>
</tr>
<tr>
<td></td>
<td>[H$_2$O$_2$]</td>
<td>0 ppb</td>
</tr>
</tbody>
</table>
surface characterization, the authors wanted to understand the basic differences in oxide films exposed to H₂O₂ and O₂ environments before determining future approaches for the characterization. Both types of test specimens are made of sensitized type 304 stainless steel, which had the chemical composition shown in Table 2. Exposure conditions are shown in Table 3.

### 3. Multilateral Surface Analyses

Instruments for multilateral surface analyses to examine the oxide film characters are listed in Table 4. Chemical forms of the oxide films were observed by X-ray diffraction (XRD) and laser Raman spectroscopy (LRS). Furthermore, elemental composition and distribution through the depth of the films were measured by Rutherford back scattering (RBS) and secondary ion mass spectroscopy (SIMS). X-ray photoelectron spectroscopy (XPS) was applied to obtain information on the nearest top surface of the oxide films. For RBS, 2.8 MeV of He²⁺ ions were injected onto the surface of the specimen and the energy of the back scattered ions was analyzed to determine oxygen concentration along the oxide depth. For SIMS, 3 keV of Cs⁺ ions were injected onto the surface of the specimen to sputter oxide in a very small spot and the secondary ions from the sputtered area were analyzed by mass spectroscopy. For XPS, monochromatic X-rays (Al-Kα: energy: 1,486.6 eV, energy width: 0.85 eV) were injected into the surface layers of the specimen, which was cleaned by exposing it to an Ar⁺ ion beam to remove surface contamination, and then photoelectrons emitted from the oxide were measured.

### III. Analytical Results

#### 1. X-ray Diffraction (XRD) and Laser Raman Spectroscopy (LRS)

Surface characterization by XRD and LRS of the specimen exposed to almost the same environmental conditions was carried out previous to this study. A comparison between XRD patterns for specimens exposed to H₂O₂ and O₂ environments is shown in Fig. 3. Clear peaks corresponding to hematite (α-Fe₂O₃) were observed for the specimen exposed to H₂O₂ while they were indistinct for O₂ exposure. At the same time, the peaks for the typical spinel of magnetite (Fe₃O₄) were observed clearly for the specimens exposed to O₂ but not for H₂O₂ exposure. Laser Raman spectroscopy was also applied to examine the surface properties of each specimen. As a result of these analyses, it was revealed that hematite (α-Fe₂O₃) was the main oxide for the specimens exposed to H₂O₂ while magnetite (Fe₃O₄) was the main oxide when exposed to O₂.

#### 2. Rutherford Back Scattering (RBS)

The RBS spectrum for each specimen type is shown in Fig. 4. The oxygen peak overlapped with the metallic atom peak in both cases. Change in energy of back scattered He²⁺ ions from the oxygen atoms is smaller than that from each of iron, nickel and chromium atoms, while that from each metallic atom is very similar due to less difference in their mass numbers. The calculated spectrum for pure iron is plotted for comparison to a measured spectrum for each specimen. The observed drop in the metallic atom signal for the

### Table 2 Chemical composition (mass%) of stainless steel used for the specimen

<table>
<thead>
<tr>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Ni</th>
<th>Cr</th>
<th>Fe</th>
</tr>
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<tbody>
<tr>
<td>0.06</td>
<td>0.42</td>
<td>0.83</td>
<td>0.028</td>
<td>0.005</td>
<td>8.41</td>
<td>18.31</td>
<td>Bal.</td>
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</table>

*Fig. 3* Comparison between X-ray diffraction patterns for test specimens exposed to H₂O₂ and O₂ environments
Table 3 Exposure conditions

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Shape (size)</th>
<th>Material</th>
<th>Exposure (concentration)</th>
<th>Temperature (K)</th>
<th>Exposure time (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Cylinder (outer diameter: 10 mm)</td>
<td>Sensitized type 304 stainless steel</td>
<td>( \text{H}_2\text{O}_2 ) (0.1–1 ppm)</td>
<td>558</td>
<td>200</td>
</tr>
<tr>
<td>B</td>
<td>Flat sheet (10×5×1 mm(^3))</td>
<td>Sensitized type 304 stainless steel</td>
<td>( \text{O}_2 ) (8 ppm)</td>
<td>558</td>
<td>200</td>
</tr>
</tbody>
</table>

Table 4 Instruments for multilateral surface analyses

<table>
<thead>
<tr>
<th>Instruments</th>
<th>Incident beam</th>
<th>Beam size</th>
<th>Incident condition</th>
<th>Detected particles</th>
<th>Obtained information</th>
<th>Location of instruments</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-ray diffraction (XRD)</td>
<td>X-rays</td>
<td></td>
<td>Energy: 50 keV</td>
<td>Diffracted X-rays</td>
<td>Chemical form of oxide (average through film)</td>
<td>[1]</td>
</tr>
<tr>
<td>Laser Raman spectroscopy (LRS)</td>
<td>Visible rays</td>
<td></td>
<td>Wavelength: 632.8 nm</td>
<td>Scattered laser</td>
<td>Chemical form of oxide (thin layers of surface)</td>
<td>[1]</td>
</tr>
<tr>
<td>Rutherford back scattering spectroscopy (RBS)</td>
<td>( \text{He}^{2+} ) 1 mmφ</td>
<td></td>
<td>Energy: 2.8 MeV</td>
<td>Back scattered ( \text{He}^{2+} )</td>
<td>Isotope distribution (through depth)</td>
<td>[2]</td>
</tr>
<tr>
<td>Secondary ion mass spectroscopy (SIMS)</td>
<td>( \text{Cs}^+ ) 500×500 μm(^2)</td>
<td></td>
<td>Energy: 3 keV</td>
<td>Cs cluster</td>
<td>Isotope distribution (through depth)</td>
<td>[3]</td>
</tr>
<tr>
<td>X-ray photoelectron spectroscopy (XPS)</td>
<td>X-rays 4×4 mm(^2)</td>
<td></td>
<td>Energy: 1.486 keV</td>
<td>Photoelectrons</td>
<td>Chemical bonding (through depth)</td>
<td>[3]</td>
</tr>
</tbody>
</table>

[1] Power & Industrial Systems R&D Laboratory, Hitachi, Ltd
[2] Institute for Materials Research, Tohoku University
[3] Institute of Multidisciplinary Research, Tohoku University.

![Graph](image)

Fig. 4 Rutherford backscattering spectra of \( \text{He}^{2+} \) for test specimens exposed to \( \text{H}_2\text{O}_2 \) and \( \text{O}_2 \) environments

measured spectrum is caused by the presence of oxygen in the oxide film. Comparing spectra for the specimens exposed to \( \text{H}_2\text{O}_2 \) (Fig. 4(a)) and \( \text{O}_2 \) (Fig. 4(b)) for channels 420–460, corresponding to the surface region showed small changes in the spectra worthy of attention. The much sharper drop observed only in the spectrum for the specimen exposed to \( \text{H}_2\text{O}_2 \) might be caused by a higher oxygen ratio in the oxide film.

By analyzing RBS spectral data, the depth profiles of the oxygen to iron ratio (O/Fe) were obtained and are shown in Fig. 5. To a depth of 0.1 μm, the specimen exposed to \( \text{O}_2 \) had a higher O/Fe ratio than that exposed to \( \text{H}_2\text{O}_2 \), while from 0.1 to 0.3 μm the specimen exposed to \( \text{H}_2\text{O}_2 \) had a much higher
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Fig. 5  Depth profiles of O/Fe in the test specimens measured by RBS

O/Fe ratio.

The O/Fe ratios in the depth region of less than 0.1 µm were in excess of 1.5, the ratio of Fe₂O₃, and 1.33, that of Fe₃O₄, and were caused by crystal water contained in the oxide film or metal hydroxide, Fe(OH)₂ or Fe(OH)₃.

3. Secondary Ion Mass Spectroscopy (SIMS)

The test specimens were sputtered by 3 keV of Cs⁺ ions, which provided high resolution mass spectroscopy not only for metallic ions, but also oxygen and hydrogen ions. The oxygen/iron (O/Fe) and hydrogen/iron (H/Fe) ratios obtained from the SIMS spectrum for each specimen are shown in Fig. 6. In the case of SIMS, measured ion currents were affected not only by elemental composition in the oxide film but also their chemical forms, which caused the difference in sputtering yield and ionizing efficiency of the oxide.

Oxide layers with a constant O/Fe ratio were observed at the surfaces of the specimens (Fig. 6(a)). The O/Fe ratio drastically decreased as the depth increased. The thickness of oxide film on the stainless steel exposed to H₂O₂ was about 0.3 µm, while that to O₂ was about 0.2 µm.

A large difference was observed in the H/Fe ratios between specimens exposed to H₂O₂ and O₂. The H/Fe ratio of specimen A (Table 3) exposed to H₂O₂ was high and decreased steeply with depth. The H/Fe ratio at the very surface of the oxide film on the specimen exposed to H₂O₂ was much higher than that at the surface of the specimen B exposed to O₂ (Fig. 6(b)). The absolute ratio could not be discussed from the SIMS data. But the difference in the surface hydrogen concentrations at the surfaces provided important information on the oxidation mechanism for both corrosive circumstances. This enriched hydrogen content might come from OH radicals, which would be generated from H₂O₂ decomposition at the oxide surface.

Figure 7 shows Cr/Fe and Ni/Fe ratios. The specimen exposed to H₂O₂ showed Cr depression in the oxide film, while the specimen exposed to O₂ had Cr enrichment in the oxide (Fig. 7(a)). No big difference in the Ni/Fe ratio was observed throughout the oxide film (Fig. 7(b)).

4. X-ray Photoelectron Spectroscopy (XPS)

Chemical bonding of each elemental component can be determined by the shift in binding energy of inner shell electrons due to their interaction with surrounding elements. Oxygen for hydroxide (OH⁻) and that for oxide (O₂⁻) can be identified by the 1–1.5 eV of energy shift in the 1s electrons of the oxygen. The energy shift of metallic elements around oxygen was measured to analyze the difference in binding energy of metallic elements and oxygen in specimens exposed to H₂O₂ and O₂. Shifts in binding energy of O1s electrons measured by sputtering oxide films with Cs⁺ ions are shown in Fig. 8.

The theoretical binding energy of O1s electrons is 531.0 eV. For specimen B exposed to O₂, the binding energy did not change with sputtering. The binding energy decreased to about 530.0 eV, which was caused by binding of oxygen atoms with metallic atoms as the oxides, Fe₂O₃ and α-Fe₂O₃. For specimen A exposed to H₂O₂, the binding energy without sputtering increased to about 531.5 eV, due to binding of oxygen atoms with hydrogen atoms as Fe(OH)₂. But the increasing energy shift was observed only at the very surface. After sputtering, the binding energy decreased to 530.0 eV.

The effect of hydrogen was observed in several atomic layers. The effect of water on the test specimen was avoided for the XPS measurements by carefully controlling the vacuum.

IV. Discussion

1. Characterization of Oxide Films

As a result of X-ray diffraction measurements of oxide films on the stainless steel specimens exposed to H₂O₂ and O₂, hematite (α-Fe₂O₃) was observed for the specimens exposed to H₂O₂, while magnetite (Fe₃O₄) was the main oxide when exposed to O₂. Higher O/metal ratios were observed at the very surface of the oxide film by RBS. But it was difficult to discriminate between crystal water in the oxide and metal hydroxide by RBS analysis.

High hydrogen concentration at the oxide surface of the specimens exposed to H₂O₂ provides important information to understand the oxidation process. Hydrogen peroxide, which is rather stable in elevated temperature water, is easily decomposed at the oxide film surface. Hydrogen peroxide decomposes into two OH radicals, which are very short lived. At the oxide surface, a well-developed magnetite film can pick up some number of OH radicals to form a complex oxide containing hydrogen which is then dehydrated to give a higher order oxide (hematite).

Hydrogen presence was confirmed by the H/Fe ratio measurements. Direct measurement of OH might give much important information on the mechanism of hydrogen pick-up of the oxide film and chemical form change. Precise measurement of the oxide surface with X-ray photoelectron spectroscopy (XPS) might provide OH concentration in the film. To obtain clearer results from the XPS analysis, test specimens with a smoother and flatter surface should be prepared. Another topic to investigate is the surface character of the oxide film from which the oxidation mechanism of stainless
steel in the presence of H$_2$O$_2$ can be identified.

2. Effects of Oxide Character on Electrochemical Corrosion Potential (ECP)

The difference in ECP of stainless steel exposed to H$_2$O$_2$ and O$_2$ is caused by the difference in chemical form of oxide films, which consist mainly of hematite ($\alpha$-Fe$_2$O$_3$) for H$_2$O$_2$ exposure and magnetite (Fe$_3$O$_4$) for O$_2$ exposure.

The difference in electric resistance of oxides causes the different in anodic polarization properties. In a previous paper, the different anodic polarization curves were proposed to evaluate the experimentally obtained ECP data for the specimens under O$_2$ and H$_2$O$_2$ environments. The authors tried to explain the difference in the anodic polarization curves by electric resistance of the oxide films.

An Evans diagram to determine ECP is shown in Fig. 9. The ECP is defined as electric potential at the intersection point of the cathodic curve and the anodic curve. The anodic polarization curve of Hishida et al. is also given in the figure, corresponding to the specimen under O$_2$ environment. When highly resistant oxide layers cover the specimen, the difference in potentials between the base metal and the surface of the oxide is caused by the anodic current and the electric resistance of the oxide layers. The anodic curve of the specimen under H$_2$O$_2$ environment can be determined by electric resistance of $\alpha$-Fe$_2$O$_3$ (hematite) layers at the surface,
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Fig. 8 Chemical binding states obtained from XPS spectra

Fig. 9 Evans diagram to determine electrochemical corrosion potential (Effects of oxide film on anodic current)

which is as follows:

\[ I_a = I(V) \text{ without surface electric resistance } \]
\[ I_a = I(V - I_a R_f) \text{ with surface electric resistance, } R_f \]
\[ I_a = I^*(V, R_f). \]

Specific resistance of magnetite (Fe₃O₄: semiconductor) is about \(10^{-4} \Omega \cdot m\), while that of hematite (Fe₂O₃: insulator) is estimated as \(3 \times 10^6 \Omega \cdot m\) (about 1/100 of that of Al₂O₃). These data are obtained by extrapolating from those measured at room temperature.

Calculated anodic polarization curves for \(10^4 \Omega/\text{cm}^2\) of \(R_f\) (oxide film thickness: 0.3 \(\mu m\)) are shown in Fig. 9. As a result of decreasing anodic current, ECP of the specimen with an oxide film increased, while corrosion current decreased.

3. Further Subjects for Oxide Characterization

A drop in chromium concentration in the oxide film on the specimens exposed to H₂O₂ was confirmed, which resulted in less corrosion resistance to enhance general corrosion of stainless steel in coolant containing H₂O₂. Opposite effects of H₂O₂ on corrosion of stainless steel should be discussed for depression of corrosion resistance due to loss of chromium in the oxide layers on the specimen exposed to H₂O₂ and decrease of corrosion current due to ECP increase by increasing electric resistance of hematite in the oxide film.

Electric resistance of oxide film should be determined for both H₂O₂ and O₂ exposed specimens to estimate the shift in anodic polarization curves due to oxide layers. At the same time, it is recommended that several anodic polarization curves should be prepared for different surface conditions to calculate ECP based on the Evans diagram.

V. Conclusions

The conclusions are summarized as follows.

1. A highly ordered oxide film was confirmed by X-ray diffraction (XRD) and Rutherford back scattering spectroscopy (RBS) measurements.
2. Depressed chromium concentration was observed at the oxide film on the specimens exposed to H₂O₂, which might cause formation of an unstable oxide film and then enhanced general corrosion.
3. Enriched hydrogen concentration at the oxide surface of the specimens exposed to H₂O₂ might be caused by pick-up of OH radicals which came from hydrogen peroxide decomposition at the oxide surface.
(4) One possible mechanism for forming highly ordered oxide at the oxide film surface of the specimens exposed to H$_2$O$_2$ was that OH radicals picked up in the oxide film formed a complex oxide containing hydrogen and then these was dehydrated to get a higher order oxide (hematite).

It was confirmed that multilateral analysis can prepare valuable information to understand the difference in oxide films of specimens exposed to H$_2$O$_2$ and O$_2$ from which the mechanism of oxidation of stainless steel under H$_2$O$_2$ exposure can be proposed. Much precise measurements should be carried out by preparing well-arranged test specimens in the high temperature, high pressure experimental loop.

Nomenclature and Abbreviation

$I(V)$, $I^*(V, R_f)$: Function of $V$ or $V$ and $R_f$

$L$: Anodic current ($A/m^2$)

$V$: Potential (V-SHE)

$R_f$: Surface electric resistance ($\Omega/m^2$)

BWR: Boiling water reactor

ECP: Electrochemical corrosion potential

HWC: Hydrogen water chemistry

IGSCC: Intergranular stress corrosion cracking

LRS: Laser Raman spectroscopy

PTFE: Polytetrafluoroethylene

RBS: Rutherford back scattering spectroscopy

SIMS: Secondary ion mass spectroscopy

XPS: X-ray photo-electron spectroscopy

XRD: X-ray diffraction

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References


