Evaluation of Nb-Base Alloys for the Divertor Structure in Fusion Reactors

J. M. Purdy
Energy Technology Division/Argonne National Laboratory
9700 S. Cass Ave., Argonne, IL 60439

J. A. Todd
Materials, Mechanical and Aerospace Engineering Department/Illinois Institute of Technology
Chicago, Illinois 60616

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ABSTRACT

Niobium-base alloys are candidate materials for the divertor structure in fusion reactors. For this application, the materials should exhibit resistance to aqueous corrosion, hydrogen embrittlement, and radiation damage and should have high thermal conductivity and low thermal expansion. Results of corrosion and embrittlement screening tests of several binary and ternary alloys in high-temperature water indicated that Nb-1Zr, Nb-5Mo-1Zr and Nb-5V-1Zr (wt.%) showed sufficient promise for further investigation. These alloys, together with pure Nb and Zircaloy-4, have been exposed to high-purity water containing a low concentration of dissolved oxygen (<12 ppb) at 170, 230, and 300°C for up to ~3200 h. Weight-change data, microstructural observations, and qualitative mechanical-property evaluations reveal that Nb-5V-1Zr is the most promising alloy at higher temperatures. Below ~200°C the alloys exhibit similar corrosion behavior.

INTRODUCTION

The corrosion behavior of several binary and ternary Nb-base alloys was investigated previously [4] to identify the most promising materials for possible use as the divertor structure in a fusion reactor with an aqueous coolant [1-3]. In this study, corrosion tests were conducted on selected alloys in high-purity deoxygenated water at 170, 230, and 300°C.

EXPERIMENTAL PROCEDURE

Details of the experimental procedures were described previously [4]. Thin sheets of pure Nb and several Nb-base alloys were sheared to approximate dimensions of 8 x 20 mm. The Nb-5V-1Zr alloy, formerly designated "Cb 753" by Cabot Corporation, was obtained from two sources. The thickness of the Nb and one lot of Nb-5V-1Zr alloy was 0.5 mm; that of the other materials was 0.8 mm. Impurity levels in the two heats of Nb-5V-1Zr differed by a factor of ~2. The composition of the materials is given in Table 1.

The surface area of each specimen was measured by an image-analysis technique. The specimens were annealed in vacuo at 1000°C for 2 h prior to exposure. The exposures were conducted in refreshed autoclave systems at 170, 230, and 300°C (±2°C) with ~100 psi overpressure (above saturation) at each temperature to maintain liquid-phase water. Corrosion tests at 300°C were performed in a Type 304 stainless steel autoclave; a Hastelloy C276 autoclave (62%Ni-16%Cr-16%Mo) was used in experiments at 170 and 230°C. The dissolved-oxygen concentration of the inlet water was maintained at <12 ppb. Each ~120-day immersion experiment was interrupted at approximately 30, 60, and 90 days for removal of specimens. Weight changes of the specimens were determined to ±1 μg. Ductility changes in the specimens were evaluated by a bend test. Zircaloy-4 was included in later tests at 170 and 230°C to compare its behavior with that of Nb-base alloys.

EXPERIMENTAL RESULTS

Weight-gain versus time-of-exposure results for pure Nb, Nb-base alloys, and Zircaloy-4 are shown in Figs. 1-4. The data were fitted to the expression \( W = A - t^n \), where \( W \) is the weight gain in g-m², \( t \) is the exposure time in hours, and \( A \) and \( n \) are empirical fitting parameters. The values of \( n \) in the power-law expression vary from ~0.3-0.7 and are denoted by the slopes of the lines in Figs. 1-4. Most of the materials gained weight at 230 and 300°C; however, weight changes for all specimens at 170°C were relatively small (<0.3 mg) and did not increase with exposure time for Nb and the Nb-base alloys.

The absence of a time dependence at 230 and 170°C in Figs. 3 and 4 can be attributed primarily to deposition of a corrosion product from the Hastelloy autoclave system on the specimens. The contribution of corrosion-product deposition to weight gain becomes less significant at 300°C (Figs. 1 and 2) because corrosion rates of the Nb-base alloys are higher by an order of magnitude and deposition may be less in a stainless steel system. Figure 5 shows energy-dispersive-electron spectra (EDS) obtained from the surface of Nb-1Zr specimens after exposure to water at 170°C for ~1000 and 3200 h, and from a platinum wire that was used to suspend test specimens in the autoclave for ~3200 h at 230°C. The heights of the Fe, Ni, and O peaks are similar for all specimens, which is a qualitative indication that levels of corrosion product contamination on the surface of all specimens were similar.

Table 1. Composition of Nb and Nb-base alloys

<table>
<thead>
<tr>
<th>Alloy</th>
<th>wt.%</th>
<th>ppm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mo</td>
<td>V</td>
</tr>
<tr>
<td>Nb1</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Nb2</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Nb-1Zr&lt;sup&gt;a&lt;/sup&gt;</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Nb-5Mo-1Zr&lt;sup&gt;a&lt;/sup&gt;</td>
<td>4.86</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Nb-5V-1Zr&lt;sup&gt;a&lt;/sup&gt;</td>
<td>&lt;0.01</td>
<td>5.76</td>
</tr>
<tr>
<td>Nb-5V-1Zr&lt;sup&gt;a&lt;/sup&gt;</td>
<td>&lt;0.01</td>
<td>5.89</td>
</tr>
</tbody>
</table>

<sup>a</sup> Concentrations of Hf, W, Ta, and Ti are <100 ppm; Mn, Cu, and Ni <50 ppm; and Mg <5 ppm.

Table 2. Composition of Zircaloy<sup>a</sup>

<table>
<thead>
<tr>
<th>Alloy</th>
<th>wt.%</th>
<th>ppm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fe</td>
<td>Cr</td>
</tr>
<tr>
<td>Zircaloy-4</td>
<td>0.23</td>
<td>0.11</td>
</tr>
</tbody>
</table>

<sup>a</sup> Concentrations of Mn, Ti, and W are <25 ppm; Cu and Ni <35 ppm.

Figure 1. Weight gain versus time for Nb in high-purity, low-oxygen water at 170, 230, and 300°C

Figure 2. Weight gain versus time for Nb-base alloys in high-purity, low-oxygen water at 300°C

Figure 3. Weight gain versus time for Nb-base alloys and Zircaloy-4 in high-purity, low-oxygen water at 230°C

Figure 4. Weight gain versus time for Nb-base alloys and Zircaloy-4 in high-purity, low-oxygen water at 170°C
The weight gain due to NiO formation observed at 700°C is less pronounced at 170°C due to less continuous hydration of NiO as observed in Figure 2. The NiO-700°C specimen exposed at 100°C for 170°C for 30 minutes shows extensive hydration due to the presence of NiO. The NiO-170°C specimen exposed at 100°C for 170°C for 30 minutes shows extensive hydration due to the presence of NiO.

Figure 2 shows the NiO-700°C specimen exposed at 100°C for 170°C for 30 minutes shows extensive hydration due to the presence of NiO. The NiO-170°C specimen exposed at 100°C for 170°C for 30 minutes shows extensive hydration due to the presence of NiO.

The NiO-700°C specimen exposed at 100°C for 170°C for 30 minutes shows extensive hydration due to the presence of NiO. The NiO-170°C specimen exposed at 100°C for 170°C for 30 minutes shows extensive hydration due to the presence of NiO.
CONCLUSIONS

The Nb-5V-1Zr and Nb-5Mo-1Zr alloys were more resistant to corrosion than pure Nb and Nb-1Zr at 230 and 300°C. Weight-gain data were consistent with measured thicknesses of NbO on the specimens, which indicates that dissolution of the oxide in water was not significant at a low flow rate in these experiments. At 170°C, corrosion of all materials in deoxygenated high-purity water was relatively low as indicated by weight-gain data and film thickness measurements. Deposition of corrosion products from the Hastelloy autoclave system contributed significantly to weight gain of the specimens at 170°C. At this temperature, the alloys could survive a 180° bend without fracture at room temperature, which indicates that embrittlement caused by pick up of hydrogen liberated by the corrosion reaction was minimal.

REFERENCES


ACKNOWLEDGMENT

B. Tani of the Argonne Analytical Chemistry Laboratory performed X-ray diffraction studies on the oxide films. D. L. Rink obtained the EDS and WDS spectra for the specimens.