Effect of anions on stress corrosion cracking behaviors of ultra-high strength steel 23Co14Ni12Cr3Mo

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Abstract: The effects of chloride, sulfate and carbonate anions on stress corrosion behaviors of ultra-high strength steel 23Co14Ni12Cr3Mo were studied by stress corrosion cracking (SCC) test method using double cantilever beam (DCB) specimens. The SCC morphology was observed by using scanning electron microscopy (SEM) and the composition of corrosion products was analyzed by using energy dispersive spectrometer (EDS). The results show that the crack propagates to bifurcation in NaCl and Na2SO4 solution, while the crack in Na2CO3 solution propagates along the load direction. The SCC rate in NaCl solution is the highest, while lower in Na2SO4 solution and little in Na2CO3 solution. From the SEM morphologies, quasi-cleavage fracture was observed in NaCl and Na2SO4 solutions, but intergranular features in Na2CO3 solution. The mechanism of anion effect on SCC of steel 23Co14Ni12Cr3Mo was studied by using full immersion test and electrochemical measurements.

Key words: 23Co14Ni12Cr3Mo; ultra-high strength steel; chloride; sulfate; carbonate; stress corrosion cracking

1 Introduction

The secondary hardening type of ultra-high strength steel 23Co14Ni12Cr3Mo has optimum combination of strength and ductility, and good resistance to corrosion and fatigue [1–2]. However, as a structural material in aerospace and other applications, the steel 23Co14Ni12Cr3Mo is susceptible to stress corrosion cracking (SCC) [3–4].

SCC behavior of a material is mainly influenced by stress and environments [5–7]. The main environmental factors which affect the corrosion behavior of steel contain sulfide ion, sulfate ion, chloride ion, carbonate ion, pH, humidity, and temperature [8–10]. For a better application in industry, most studies are focused on the stress corrosion behavior in solutions containing anions such as chloride ion [11–12], sulfate ion [13–14], carbonate ion [15–16], and the comprehensive affection of environmental factors [17–18]. RODRIGUEZ et al [17] studied the stress corrosion cracking susceptibility of the AISI410 steel in steam turbine environments using electrochemical noise, which showed that the stress corrosion of AISI410 steel was caused by a comprehensive effect of pH, sulfate and chloride. ALMUBARAK et al [18] studied the stress corrosion cracking of sensitized austenitic stainless steels in Kuwait petroleum refineries, which demonstrated that SCC is more severe in polyphonic acid than in chloride and sour solutions.

Due to the high strength, the studies of 23Co14Ni12Cr3Mo steel were focused on hydrogen embrittlement [19–22]. Hydrogen diffusivity rate and transport form of 23Co14Ni12Cr3Mo steel were tested [19–20]. Hydrogen embrittlement were induced by both the outer hydrogen in environment and the inner hydrogen [21–22]. Hydrogen entered the steel and formed hydrogen traps, which reduced the susceptibility of the steel to SCC. However, the effect of environmental anions on SCC behavior of 23Co14Ni12Cr3Mo steel has little been mentioned.

In previous work, LIU et al [23] and WU et al [24] studied the stress corrosion behavior of 23Co14Ni12Cr3Mo steel by using constant load method and slow strain rate method. The fracture time in constant load and slow strain load of stress corrosion were measured to evaluate the susceptibility to SCC of 23Co14Ni12Cr3Mo steel. In the present work, the effects of chloride, sulfate and carbonate anions on stress corrosion behaviors of steel 23Co14Ni12Cr3Mo by stress corrosion cracking test method using double cantilever beam(DCB) specimens, and the effect mechanism were discussed by immersion test and electrochemical measurements.
2 Experimental

Specimens of steel 23Co14Ni12Cr3Mo were cut from a forged and annealed bar, which was heat treated as follows: solution treated in vacuum at 885 °C for 1 h, air cooled to room temperature for 2 h, chilled at −73 °C for 1 h, and tempered at 482 °C for 5 h. The chemical compositions (mass fraction) were as follows: 0.23% C, 13.4% Co, 11.1% Ni, 3.1% Cr, 1.2% Mo, Fe for balance. Its relevant mechanical properties are given in Table 1.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>σb/MPa</td>
<td>1960</td>
</tr>
<tr>
<td>σ0.2/MPa</td>
<td>1690</td>
</tr>
<tr>
<td>δ5/%</td>
<td>14</td>
</tr>
<tr>
<td>ψ/%</td>
<td>68.5</td>
</tr>
<tr>
<td>KIC/ (MPa·m1/2)</td>
<td>136</td>
</tr>
</tbody>
</table>

The DCB specimen (26 mm×26 mm×127 mm with notch length of 33 mm) was cut, as shown in Fig. 1. The specimens were pre-cracked at 20 Hz by fatigue test machine (MTS880, America) before loaded by bolts. The initial crack length was about 2−4 mm.

![Fig. 1 DCB specimens of steel 23Co14Ni12Cr3Mo (Unit: mm)](image)

The specimens were placed in 0.5 mol/L NaCl solution, 0.5 mol/L Na2SO4 solution, 0.5 mol/L Na2CO3 solution separately at room temperature for SCC tests. Observations were carried out about every 12−24 h, which depended on the crack propagation rate. The SCC test was terminated when the crack propagated path closed to a side edge of the specimen or the crack path propagated where the crack growth rate became negligible. After SCC testing, the specimens were fractured and the crack planes were examined by using SEM (Cambridge 3400, England) and EDS (Cambridge 3400, England). Specimens tested in air were also fractured and examined using EDS for comparison. The corrosion products bladed off along the crack propagation path were characterized by using XRD (D/MAX-2200PC, Japan).

In order to study the anion effects on SCC behavior, specimens without load were immersed in 0.5 mol/L NaCl solution, 0.5 mol/L Na2SO4 solution, 0.5 mol/L Na2CO3 solution separately at room temperature for 168 h and characterized by SEM and electrochemical methods. The specimens which embedded in epoxy resin with an exposure area of about 0.7854 cm² were immersed in 0.5 mol/L NaCl solution, 0.5 mol/L Na2SO4 solution, 0.5 mol/L Na2CO3 solution respectively for 168 h. The electrochemical measurements for specimens with and without immersions were carried out on an electrochemical system (VersaSTAT MC, Princeton Applied Research). The steel, a platinum sheet and a saturated Calomel electrode (SCE) were served as the working electrode, the counter electrode and the reference electrode, respectively. Before EIS measurement, the open circular potential was recorded for 30 min. The EIS measurement frequency ranged from 100 kHz to 0.01 Hz with applied AC perturbation of 10 mV. The impedance data were analyzed by a commercial ZSimpWin software package. The polarization curves were measured at a potential scan rate of 5 mV/min. The potential ranged from −0.25 V (vs OCP) to 0.25 V (vs OCP).

3 Results and discussion

3.1 Effect of anions on SCC path

The SCC propagation paths of steel 23Co14Ni12Cr3Mo in three solutions are shown in Figs. 2−4. It is found that the crack propagates to bifurcation in NaCl and Na2SO4 solutions, while the crack propagates along the load direction in Na2CO3 solution. The crack in NaCl solution propagates along the center line (24 h) and then forms a bifurcation, which propagates in the vertical direction against the load direction with the test time. When testing for 168 h, the crack path propagates to another bifurcation at the crack tip. The crack in Na2SO4 solution propagates to bifurcations (24 h), and develops along the crack tip until failure. The crack in Na2CO3 solution propagates along the loading direction for about 0.8 mm in the whole propagation process.

Figure 5 shows the optical morphologies of fracture surface along the crack propagation by optical microscopy. The SCC path is from right to left in the figures. Serious corrosion happens in prophase of crack propagation, while obvious in metaphase and slight in anaphase in NaCl solution. From the corrosion morphology on the fracture surface, the crack is close to the transverse edge of the specimen in NaCl solution. Corrosion in pre fatigued tip is serious, and corrosion also appears in the propagation zone in Na2SO4 solution. The crack is close to the middle transverse of the specimen in Na2SO4 solution. Little corrosion occurs in Na2CO3 solution. It suggests that the crack propagates little.