LOCALIZED CORROSION AND STRESS CORROSION CRACKING
CHARACTERISTICS OF A LOW-ALUMINUM-CONTENT IRON-ALUMINUM ALLOY

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J. G. Kim and R. A. Buchanan

ABSTRACT

The aqueous corrosion behavior of FAPY, a non-ordered Fe-Al alloy (Fe-16.1Al-5.4Cr-1.1Mo-0.11C-0.11Zr-0.06Y, at. %), was studied in various electrolytes and compared with reference materials. Corrosion rates for FAPY were much closer to that of 304L stainless steel than to the plain-carbon and low-alloy steels evaluated. Three-week crevice corrosion tests were performed in chloride-containing solutions on FAPY, and for comparison, on the Fe₃Al-based iron aluminide FAL-Mo, and 304L stainless steel. The FAPY alloy was less resistant to crevice corrosion than FAL-Mo and 304L stainless steel. In the 3.5 wt. % NaCl solution, the FAPY alloy was subject to severe crevice corrosion. Slow-strain-rate corrosion tests were conducted at the free-corrosion potential and at potentiostatically-controlled anodic and cathodic potentials to evaluate the environmental-embrittlement susceptibility. It was found that the FAPY alloy was susceptible to hydrogen embrittlement and anodic-dissolution stress corrosion cracking, but at the free-corrosion potential and the hydrogen-producing-cathodic potentials, the ductilities were significantly higher than those for Fe₃Al-based iron aluminides.

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INTRODUCTION

Iron aluminides based on the Fe_3Al stoichiometry possess excellent resistance to high-temperature oxidation and sulfidation. However, a deterrent to their commercialization is the limited room-temperature ductility. Investigations have shown the low ductility to be caused by hydrogen embrittlement which occurs due to the reaction of water vapor with active aluminum.¹⁻³ Recent studies at the Oak Ridge National Laboratory (ORNL) have shown that the environmental-embrittlement effect can be minimized by reducing the aluminum content from its Fe_3Al -based value of 28 at. % to a value of 16 at. %, which places the new alloys in the disordered phase field.⁴ The new lower-Al Fe-Al alloys are described as possessing room-temperature ductilities in excess of 25 %, while retaining good high-temperature oxidation and sulfidation resistance. The objective of the present study was to investigate the aqueous corrosion and stress corrosion cracking behaviors of one of the new low-Al Fe-Al alloys.

PROCEDURES AND RESULTS

The new low-Al Fe-Al alloy investigated was designated as FAPY by ORNL and consisted of Fe-16.1Al-5.4Cr-1.07Mo-0.11C-0.11Zr-0.06Y (at. %). Material was in the form of sheet, and prior to testing, specimens were annealed in air for 1 hour at 800 °C and air cooled. In addition to the FAPY alloy, and depending on the specific evaluation, the following materials were evaluated for comparison: AISI 1010 plain-carbon steel, A387-G22 2 1/4 Cr - 1 Mo low-alloy steel, AISI 304L stainless steel, and the Fe_3Al -based iron aluminides, FA-84 (Fe-28Al-2Cr-0.05B, at. %), FA-129 (Fe-28Al-5Cr-0.5Nb-0.2C, at. %), and FAL-Mo (Fe-28Al-5Cr-1Mo-0.08Zr-0.04B, at. %). All specimens were ground through 600 grit SiC paper prior to testing.

Anodic Polarization Behaviors

Cyclic anodic polarization evaluations were performed on FAPY, and for comparison on the plain-carbon, low-alloy and stainless steels. Tests were conducted in the following electrolytes: distilled water (plus 0.01 wt. % Na_2SO_4 to provide adequate conductivity), tap water (approximately 15 ppm Cl^-), a mild acid-chloride solution (200 ppm Cl^- , pH=4), a 3.5 wt. % NaCl solution (pH $\approx$ 7) and 1 N NaOH. An EG&G Model 273 potentiostat was employed to conduct the polarization tests at a scan rate of 600 mV/h. Each solution was aerated by sparging with pure oxygen before as well as during the test. The results are shown in Figures 1-5.

In the distilled water (Figure 1), the plain-carbon and low-alloy steels exhibited active corrosion, i.e., no passivation, whereas the FAPY alloy and the stainless steel exhibited passivation to very high potentials. The polarization behaviors in tap-water (Figure 2) showed no significant differences compared to those in distilled water, except that FAPY demonstrated a large hysteresis loop indicating susceptibility to localized corrosion. In the mild acid-chloride solution (Figure 3), the plain-carbon and low-alloy steels underwent active corrosion only, whereas the FAPY alloy and the stainless steel remained passivated to their respective breakdown potentials. The corrosion, breakdown and protection potentials were higher for the stainless steel than for the FAPY alloy. In the much-higher-chloride 3.5 wt. % NaCl solution (Figure 4), again the plain-carbon and low-alloy steels underwent active corrosion only; however, the FAPY alloy and the stainless steel remained passivated to their respective breakdown potentials. The breakdown and protection potentials were higher for the stainless steel than for the FAPY alloy. Comparing the results in the mild acid-chloride solution (Figure 3) and the 3.5 wt. % NaCl solution (Figure 4), the breakdown and protection potentials for both the FAPY alloy and the stainless steel decreased in the 3.5 wt. % NaCl solution due to the higher chloride concentration. In the highly-basic 1N NaOH solution (Figure 5), all of the materials exhibited very similar and excellent corrosion behavior by passivating to high potentials. Overall, the polarization behavior of the FAPY alloy was much closer to that of the 304L stainless steel than to the plain-carbon and low-alloy steels.

Fig. 1. Cyclic anodic polarization curves in aerated distilled water.

Fig. 2. Cyclic anodic polarization curves in aerated tap-water.

Fig. 3. Cyclic anodic polarization curves in aerated 200 ppm Cl^- (pH=4) solution.

Fig. 4. Cyclic anodic polarization curves in aerated 3.5 wt.% NaCl solution.

Fig. 5. Cyclic anodic polarization curves in aerated 1N NaOH solution.

Corrosion Rates

Corrosion rates were determined by two different methods: the electrochemical polarization-resistance method, which provided corrosion rates over approximately the first two hours of exposure, and a three-week immersion test method, whereby corrosion rates were calculated from weight-loss measurements and represented three-week-average corrosion-rate values. The same materials and electrolytes were evaluated as described in the previous section on polarization behavior. The results are given in Table 1.

As seen in Table 1, the corrosion rates determined by the polarization-resistance method (initial exposure values) were generally higher than those determined by the weight-loss method (three-week average values), indicating that the corrosion rates decreased with time. In the distilled water, tap water, mild acid-chloride solution, and 3.5 wt. % NaCl solution, the corrosion rates for the FAPY alloy and the 304L stainless steel were similar and

much lower than those of the plain-carbon and low-alloy steels. In the highly-basic NaOH solution, the corrosion rates were quite low for all of the materials.

Table 1. Results of corrosion rate measurements.

Solution	Material	Average Penetration Rates (mpy)	
		Polarization Resistance	Three-Week Immersion
Distilled Water	1010	12.1	3.9
	21/4Cr-1Mo	6.3	3
	FAPY	<0.1	<0.1
	304L SS	<0.1	<0.1
Tap Water	1010	0.93	4.5
	21/4Cr-1Mo	1.9	2.2
	FAPY	<0.1	<0.1
	304L SS	<0.1	<0.1
200 ppm Cl ⁻ pH=4	1010	56	4.8
	21/4Cr-1Mo	20	3.6
	FAPY	2.3	<0.1
	304L SS	<0.1	<0.1
3.5 wt. % NaCl	1010	40	3.8
	21/4Cr-1Mo	39	3.2
	FAPY	0.19	<0.1
	304L SS	<0.1	<0.1
1M NaOH	1010	0.53	<0.1
	21/4Cr-1Mo	0.59	<0.1
	FAPY	0.38	<0.1
	304L SS	0.14	<0.1

Crevice Corrosion Behaviors

Three-week crevice-corrosion tests were conducted on the FAPY alloy, and, for comparison, on the Fe₃Al-based iron aluminide, FAL-Mo, and on 304L stainless steel, using multiple crevice assemblies⁵ which formed 60 crevice sites on each specimen. The tests were performed in the mild acid-chloride solution (200 ppm Cl⁻, pH=4) and in the 3.5 wt. % NaCl solution. The results are given in Table 2.

In the mild acid-chloride solution, the percentages of crevice sites that underwent active crevice corrosion were 8 % for the FAPY alloy, 0 % for FAL-Mo, and 2 % for the stainless steel. The FAPY and 304L stainless steel specimens after exposures in the mild acid-chloride solution are shown in Figure 6. In the higher-chloride 3.5 wt. % NaCl solution, the percentages of sites that underwent active crevice corrosion were 100 % for the FAPY alloy, 8 % for FAL-Mo, and 3 % for the stainless steel. The FAPY and 304L stainless steel specimens after exposures in the 3.5 wt. % NaCl solution are shown in Figure 7. The degree of crevice corrosion increased significantly with increasing Cl^- concentration for the FAPY alloy. Overall, the resistance to crevice corrosion in chloride environments for the FAPY alloy was considerably less than that of the FAL-Mo iron aluminide and the 304L stainless steel.

Table 2. Three-week immersion test results for creviced specimens in 200 ppm Cl^- (pH=4) and 3.5 wt. % NaCl solutions.

Solution	Measurement	Material		
		FAP-Y	FAL-Mo	304L SS
200 ppm Cl^- , pH=4	No. of Crevice Sites Attacked (60 max.)	5	0	1
	Percentage of Sites Attacked	8	0	2
	Max. Depth of Attack (μm)	80	0	4
3.5 wt.% NaCl, pH=7	No. of Crevice Sites Attacked (60 max.)	60	5	2
	Percentage of Sites Attacked	100	8	3
	Max. Depth of Attack (μm)	50	50	4

Fig. 6. Photographs of FAPY and 304L stainless steel crevice-corrosion specimens after three-week exposures in 200 ppm Cl^- (pH=4) solution.

304L

FAPY

Fig. 7. Photographs of FAPY and 304L stainless steel crevice-corrosion specimens after three-week exposures in 3.5 wt. % NaCl solution.

304L

FAPY

Slow-Strain-Rate Behaviors

Slow-strain-rate tests were performed on the FAPY alloy in the mild acid-chloride solution at a strain rate of 1.2×10^{-6} /s at the free-corrosion potential (E_{corr}) and at potentiostatically-controlled anodic and cathodic potentials. Tests were also performed in air for comparison. The specimens, with gage sections of 12.7 x 1.78 x 0.63 mm, were polished with 600 grit SiC paper after heat treatment and prior to testing. The results are given in Table 3.

The highest slow-strain-rate ductilities for FAPY were observed at E_{corr} and -200 mV(SHE), and these ductilities were comparable to that observed in laboratory air. Embrittlement associated with pitting corrosion occurred at the applied anodic potentials (+300 and +500 mV(SHE)) and embrittlement associated with hydrogen occurred at the applied hydrogen-producing cathodic potentials (-1000 and -1500 mV(SHE)). The fracture surfaces were analyzed by scanning electron microscopy, and the resultant fractographs for the specimens tested at the various potentials are shown in Figures 8 - 10. As shown in Figure 8, at the anodic potential of +500 mV(SHE), the cracking was mostly by the brittle intergranular mode with some transgranular cleavage, whereas at the anodic potential of +300 mV(SHE), the cracking was mostly by the brittle transgranular cleavage mode. As shown in Figure 9, at the free-corrosion potential, E_{corr} , and at the cathodic potential of -200 mV(SHE), the cracking was by the ductile microvoid coalescence mode. As shown in Figure 10, at the cathodic potentials of -1000 and -1500 mV(SHE), both of which produced large amounts of hydrogen at the specimen surfaces, the cracking was again by the brittle transgranular cleavage mode.

Table 3. Slow-strain-rate test results for FAPY in the mild acid-chloride solution.

Applied Potential (mV vs SHE)	Time to Fracture (hr.)	Fracture Stress (MPa)	Percent Elongation
+500	8.3	110	2.4
	--	--	2.3
+300	20.5	510	3.2
	39.5	607	6.3
E _{corr}	55	634	13.4
	--	--	17.3
-200	59	696	15.0
	43	558	11.0
-1000	26.5	610	4.7
-1500	26.7	552	4.7
	--	--	4.7
Air	34	758	14.2
	--	--	14.2

+500 mV(SHE)

+300 mV(SHE)

Fig. 8. Fracture surfaces of FAPY after slow-strain-rate testing in 200 ppm Cl^- (pH=4) solution at anodic potentials of +500 and +300 mV(SHE).

Fig. 9. Fracture surfaces of FAPY after slow-strain-rate testing in 200 ppm Cl⁻ (pH=4) solution at the free-corrosion potential, E_{corr} , and the cathodic potential of -200 mV(SHE).

-1000 mV(SHE)

-1500 mV(SHE)

Fig. 10. Fracture surfaces of FAPY after slow-strain-rate testing in 200 ppm Cl^- (pH=4) solution at cathodic potentials of -1000 and -1500 mV(SHE).

The slow-strain-rate ductilities for the FAPY alloy (16 % Al) in the mild acid-chloride solution are compared in Figure 11 with those of previously-evaluated FA-84 and FA-129, two Fe₃Al-based iron aluminides (28 % Al). The trends in behavior for all three materials were similar; however, the ductilities at the free-corrosion and cathodic potentials were significantly greater for the FAPY alloy in comparison to the Fe₃Al-based iron aluminides.

Fig. 11. Ductilities of FAPY, FA-84 and FA-129 under slow-strain-rate conditions in 200 ppm Cl⁻, pH = 4 solution as a function of potential.

SUMMARY AND CONCLUSIONS

A low-aluminum-content iron-aluminum alloy developed at ORNL, FAPY (Fe-16.1Al-5.4Cr-1.07Mo-0.11C-0.11Zr-0.06Y, at. %), was evaluated in various electrolytes at room temperature to determine polarization behaviors, corrosion rates, crevice corrosion behaviors, and slow-strain-rate embrittlement characteristics. Reference materials were also evaluated for comparison. The results and conclusions are summarized as follows:

- With regard to cyclic-anodic-polarization behavior, both the FAPY alloy and 304L stainless steel passivated to relatively high potentials in distilled water, tap water, a 200 ppm Cl^- (pH = 4) solution and a 3.5 wt. % NaCl solution, whereas 1010 plain-carbon steel and 2 1/4 Cr - 1 Mo low-alloy steel underwent only active corrosion. All four materials passivated in a highly-basic 1 N NaOH solution.
- In terms of surface-average corrosion rates, as determined by electrochemical polarization-resistance measurements and weight-loss measurements, the FAPY alloy behaved much more like 304L stainless steel than the plain-carbon and low-alloy steels in the distilled water, tap water and the two chloride solutions. In the NaOH solution, all four materials exhibited very low corrosion rates.
- With regard to crevice-corrosion behavior in a 200 ppm Cl^- (pH = 4) solution and a 3.5 wt. % NaCl solution, the FAPY alloy was found to be less resistant than both an Fe_3Al -based iron aluminide, FAL-Mo (Fe-28Al-5Cr-1Mo-0.08Zr-0.04B, at. %), and 304L stainless steel.
- In terms of slow-strain-rate ductilities in the 200 ppm Cl^- (pH = 4) solution, the FAPY ductility was found to be significantly higher than the two Fe_3Al -based iron aluminides evaluated, FA-84 (Fe-28Al-2Cr-0.05B, at. %) and FA-129 (Fe-28Al-5Cr-0.5Nb-0.2C, at. %), at the free-corrosion potentials and at hydrogen-producing cathodic potentials.

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