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STRESS-CORROSION CRACKING OF A
URANIUM 6-WEIGHT PERCENT NIOBIUM ALLOY

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SUBJECT DESCRIPTORS

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STRESS-CORROSION CRACKING OF A URANIUM 6-WEIGHT PERCENT NIOBIUM ALLOY

Robert L. Kochen, Richard Mah, and Ross J. Jackson

Abstract. The stress-corrosion cracking (SCC) behavior of the uranium 6-weight percent niobium (U 6-wt % Nb) alloy in three different heat-treated conditions was investigated. The three heat treatments were: (a) solution quenched (the nonaged condition); (b) solution quenched and aged 6 hours at 250 °C (the underaged condition); and (c) solution quenched and aged 80 minutes at 600 °C (the overaged condition). The SCC tests utilized smooth, dead-weight loaded, static tensile specimens exposed to nitrogen-saturated or oxygen-saturated water containing 50 parts per million (ppm) chloride ions. The alloy in the solution-quenched condition was not susceptible to SCC when loaded to 90 percent of yield strength in either the oxygen or nitrogen-saturated chloride solutions. The underaged material (6 hours at 250 °C) was susceptible to SCC in oxygen or nitrogen-saturated water containing 50 ppm chloride ions. The underaged material was more susceptible to cracking in the oxygen-saturated solution than in the nitrogen-saturated solutions. The SCC in the underaged material proceeded by a principally intercrystalline fracture mode with the overload condition being principally transgranular. The overaged material also exhibited SCC, but to a lesser extent than the underaged material. Here again, cracking was more pronounced in the oxygen-saturated solution than in the nitrogen-saturated solution. The overaged material fractured by a combined SCC mode and mechanical-cracking mode, i.e., stress-corrosion cracks were growing at the same time corrosion was reducing the cross-sectional area of the specimen. The importance of knowing alloy characteristics relates to considerations of design, environmental behavior, and economics.

INTRODUCTION

The uranium 6-weight percent niobium (U 6-wt % Nb) alloy is an economical, high density [17.4 grams per

cubic centimetre (g/cm^3)], engineering alloy possessing good corrosion resistance. The alloy can be solution-quenched from the single-phase gamma region (750 to 1100 °C) to yield a supersaturated, single-phase, monoclinic, alpha-prime solid solution. The solution-quenched alloy is in the soft condition and can be strengthened by aging in the alpha plus gamma₂ ($\alpha + \lambda_2$) two-phase region (150 to 640 °C). The equilibrium phase relationships involved are discussed by Rogers *et al.* (1) and by Pfeil *et al.* (2).¹ The nonequilibrium phase relationships are given by Anagnostidis *et al.* (3), Tangri and Chaudhuri (4), D'Amato *et al.* (5) and Jackson (6). The strengths of the quenched and aged alloys are discussed by Jackson and Miley (7). The corrosion behavior of the alloy is discussed by Waber (8) and by Macki and Kochen (9, 10).

Uranium alloys, as a general rule, are subject to stress-corrosion cracking in several environments, including air, especially in the strengthened (aged) conditions. Minimum yield strengths of 120,000 psi [840 megapascals (MPa)] and elongations of 10 percent or greater were required. The strength requirements could be achieved by solution quenching from the gamma-phase field followed by either underaging or overaging in the $\alpha + \lambda_2$ two-phase region. The U 6-wt % Nb alloy in this application also had to have maximum resistance to stress-corrosion cracking. Thus, this study was to evaluate and compare stress-corrosion properties of the underaged and overaged material. The solution-quenched material was also evaluated, since certain design modifications did not require the high strengths of the aged alloy.

LITERATURE SURVEY

Several reports (11 through 22) are available on the stress-corrosion behavior of uranium-niobium

¹ Numerals in parentheses relate to references at end of text.

alloys. Tragert (11) sought the SCC mechanism for several reactor materials (including U-Nb alloys). Orman (12) developed a rapid test for determining susceptibility to SCC and applied the test to several alloys, one of which was the U 6-wt % Nb alloy. Stephenson (13) studied metallurgical and electro-chemical variables on the initiation phase of stress-corrosion cracking for the U 4.5-, U 6.5-, and U 8.5-wt % Nb alloys. Bend specimens, immersed in aqueous solutions and held at constant potentials, were used to investigate the stress-corrosion crack initiation characteristics of the three U-Nb alloys.

Magnani *et al.* (14, 18) looked at the effect of chloride ions on the cracking behavior of the U 4.5-wt % Nb alloy. A fracture mechanics approach to the problem showed that chloride-ion concentration strongly affects both the crack velocity and the fracture mode. Three concentrations were investigated: <2, 50, and 500 parts per million (ppm) chloride ions. For the <2 and 50 ppm Cl^- solutions, stress-intensity thresholds of 14 to 17 $\text{ksi} \cdot (\text{inch})^{1/2}$ [15 to 19 $\text{MPa} \cdot (\text{m})^{1/2}$] were observed. At the 500 ppm Cl^- level, stress-corrosion cracking was observed without the application of stress. This was attributed to corrosion-product wedging. Magnani *et al.* (15) in another report looked at the stress-corrosion cracking behavior of tungsten-filament-reinforced U 4.5-wt % Nb alloy in 100 percent relative-humidity air. Units for fracture toughness value are expressed in thousand pounds per square inch $\cdot (\text{inch})^{1/2}$ [$\text{ksi} \cdot (\text{inch})^{1/2}$] and translate for metric use to megapascals $\cdot (\text{metre})^{1/2}$ [$\text{MPa} \cdot (\text{m})^{1/2}$].

McLaughlen *et al.* (16) studied the effect of aging on the susceptibility of the U 5-wt % Nb alloy to stress-corrosion cracking. Their results showed that optimum resistance to the initiation of stress-corrosion cracks can be obtained by aging above 550 °C. The aging treatments in this range produced a microstructure resistant to stress-corrosion cracking and the alloy also had good tensile and ductility properties measured in air. For example, an alloy aged for 8 hours at 600 °C possessed an ultimate tensile strength of 160 ksi [1,120 megapascals (MPa)] with 17 percent elongation.

Magnani (17) reported on the effects of environment on the cracking behavior of several uranium alloys.

His results showed that all of the alloys (including U 4.5-wt % Nb) stress-corrosion cracked in laboratory air and that aqueous solutions containing chloride ions were considerably more hostile. Magnani indicates that the observed transgranular cracking is caused by a two-stage mechanical stress-corrosion cracking mechanism, involving either oxidation at the crack tip and then rupture of the film or the base material below the film or the absorption of oxygen at the crack tip and then rupture of the weakened matrix material.

Macki and Kochen (19) studied the stress-corrosion cracking behavior of the U 4.2-wt % Nb alloy aged 80 hours at 260 °C. Smooth four-point bend SCC tests and smooth static-tensile SCC tests were used. The results of this study showed that the aged U 4.2-wt % Nb alloy was susceptible to SCC when stressed and exposed to water containing oxygen and chloride ions. The stress-corrosion cracks which nucleated in the aqueous chloride environments proceeded by an intergranular SCC fracture mode. No failures were observed in dry air containing less than 200 ppm moisture or in 100 percent relative humidity air. The surface tensile stress required for SCC was less than 20,000 pounds per square inch (psi) (140 MPa) in oxygen-saturated water containing 50 ppm chloride ions.

Magnani *et al.* (20) observed the stress-corrosion cracking behavior of U 4.5-wt % Nb in about 10 percent relative humidity air using side-grooved, tapered, double-cantilevered-beam specimens. Crack propagation was monitored using crack opening displacement gauges and acoustic emission detection techniques. The threshold stress intensity for stress-corrosion cracking was determined to be approximately 20 $\text{ksi} \cdot (\text{inch})^{1/2}$ [22 $\text{MPa} \cdot (\text{m})^{1/2}$] and the plane strain fracture toughness approximately 50 $\text{ksi} \cdot (\text{inch})^{1/2}$ [55 $\text{MPa} \cdot (\text{m})^{1/2}$].

Macki and Kochen (21) looked at the stress-corrosion cracking (SCC) behaviors of the U 2.3-wt % Nb alloy aged 24 hours at 230 °C (underaged) and 24 hours at 430 °C (overaged). The SCC test utilized smooth, dead-weight loaded, static-tensile specimens which were exposed to oxygen-saturated water containing 50 ppm chloride ions. The tests showed that the underaged material was more susceptible to SCC than the overaged material.

FIGURE 1. Static-tensile, stress-corrosion cracking specimen and environmental chamber.

The SCC in the underaged material proceeded by a transgranular fracture mode. The overaged material did not fracture by an SCC mode; but rather, by a mechanical mode after corrosion had reduced the cross-sectional areas of the specimens.

Magnani and Romero (22) exposed the U 4.5-wt % Nb alloy to water-saturated nitrogen and oxygen to determine the rate of reaction of water vapor with the alloys. The data showed that the alloy reacted more slowly than uranium and that oxygen inhibited the reaction. Stress-corrosion tests were also conducted to determine the effects of the environment on the cracking behavior. In moist environments, the data showed that the U 4.5-wt % Nb alloy does stress-corrosion crack in either nitrogen or air.

DISCUSSION

Experimental:

Smooth, dead-weight loaded, static tensile, stress-corrosion cracking tests were used to compare the

susceptibility to stress corrosion cracking of the underaged, overaged, and solution quenched U 6-wt % Nb alloy. The test specimens were round, 4-inch [10.2-centimetres (cm)] long tensile test types with a reduced cross-sectional diameter of 0.253 inches (0.64 cm). The reduced section was 2.75 inches (6.98 cm) long connected by a 0.25-inch (0.64 cm) radius fillet to threaded 0.375 inches (0.95 cm) diameter ends. A static-tensile test specimen is shown unmounted and also in an environmental test chamber in Figure 1.

The environmental test chamber (Figure 1) was of 1.5-inch (3.8-cm) diameter Pyrex tubing with a gas inlet, gas exit, and fill tube. The end caps were of Nylon and were sealed to the Pyrex and the test specimen with a silicone rubber, Dow Corning 3145 RTV®. This sealant was chosen because of its elasticity and because chloride ions are not leached from it by aqueous solutions.

Each specimen and chamber were mounted on a stressing device which works by means of lead bricks loaded onto the end of a lever beam, as shown in Figure 2. First the test solution, water

FIGURE 2. Stress-corrosion cracking specimen and environmental chamber mounted in stressing device.

containing a predetermined amount of chloride ions, was introduced into the chamber. Second, nitrogen or oxygen was bubbled through this solution for one hour to achieve saturation. Finally, the load was applied. The dissolved oxygen concentration in the nitrogen-saturated water was not measured.

A 50-ppm chloride ion concentration was achieved by adding reagent grade sodium chloride (NaCl) to distilled water. The chloride-ion concentration was determined by using an Ionalyzer® Model-801 digital pH meter with a Model-94-17A Ionalyzer chloride-ion electrode and a Model-90-01 Ionalyzer single-junction reference electrode. All of the distilled water plus sodium chloride solutions had initial chloride-ion concentrations of 50 ppm $\pm$ 1.

Stress levels for the solution-quenched specimens were 0, 11, 16, 21.5, and 24 ksi (0, 77, 112, 150, and 168 MPa, respectively). The underaged and overaged specimens were stressed at 0, 48, 72, 96,

and 108 ksi (0, 336, 504, 672, and 756 MPa, respectively). In all cases, these stress levels represent 0-, 40-, 60-, 80-, and 90-percent yield strength of the U 6-wt % Nb alloy at room temperature (26 °C $\pm$ 2).

As mentioned earlier, the strength requirements for the underaged and overaged material was a 0.2-percent offset yield strength of 120 ksi (840 MPa) with a minimum of 10 percent elongation. These requirements were roughly met by underaging the U 6-wt % Nb alloy for 6 hours at 250 °C, and by overaging for 80 minutes at 600 °C. The solution-quenched material had a yield strength of 27 ksi (189 MPa) and an elongation of 25 percent. The properties of the underaged, overaged, and solution-quenched material are listed in Table I. After completion of the SCC tests, the Analytical Laboratory examined samples from two each of the underaged, overaged, and solution-quenched SCC specimens. The results are shown in Table II.

TABLE I. Typical mechanical properties for the solution-quenched, underaged, and overaged uranium 6-weight percent niobium alloy.

Property	Solution Quenched	Underaged (6 hours at 250 °C)	Overaged (80 minutes at 600 °C)
	(pounds per square inch)		
Yield Strength (0.2-percent offset)	27×10^3	120×10^3	120×10^3
Ultimate Tensile Strength	115×10^3	165×10^3	185×10^3
Elastic Modulus	9×10^6	11×10^6	21×10^6
Percent Reduction of Area (RA)	30 percent	20 percent	25 percent
Percent Elongation	25 percent	12 percent	12 percent
Hardness	DPN 160 R _A 58	R _A 70	R _A 72
Impact Strength	60 foot-pounds force (80 joules)		

TABLE II. Results of chemical analysis on uranium 6-weight percent niobium specimens (parts per million).

Sample	Carbon	Nitrogen	Oxygen	Hydrogen	Niobium (weight percent)
Underaged	140	120	37	4.4	6.4
Underaged	140	120	42	4.4	6.1
Overaged	140	110	46	4.6	6.3
Overaged	140	110	37	5.2	6.2
Solution Quenched	150	110	37	4.2	6.1
Solution Quenched	120	110	33	3.8	6.1

Results:

Smooth, static-tensile SCC tests were used to compare the SCC behaviors of the underaged, overaged, and solution quenched U 6-wt % Nb alloy. A smooth specimen SCC test involves stressing the specimen in a test environment and recording the Time-to-Failure (T-F). This T-F is the sum of the crack nucleation time and the crack propagation time.

The results of the static-tensile SCC tests on the U 6-wt % Nb alloy are summarized in Tables III and IV. The results for the underaged alloy in O₂ - H₂O - Cl⁻ and N₂ - H₂O - Cl⁻ environments are shown graphically in Figures 3 and 4, respectively; while the results for the overaged alloy in O₂ - H₂O - Cl⁻ and N₂ - H₂O - Cl⁻ environments are shown in Figures 5 and 6, respectively. In Figure 7, a comparison is shown of results for the solution-quenched, underaged, and overaged alloys in the two environments.

TABLE III. Results of the stress-corrosion cracking tests on uranium 6-weight percent niobium.

Sample	Stress (pounds per square inch × 1000)	^d Environment	Time-to-Failure (hours)	Test Time on Remaining Specimens ^k (hours)
^a Underaged	0	^e O ₂ - H ₂ O - Cl ⁻	^g	None
Underaged	0	^f N ₂ - H ₂ O - Cl ⁻	^h	None
Underaged	24	O ₂ - H ₂ O - Cl ⁻		8760, 8760
Underaged	48	N ₂ - H ₂ O - Cl ⁻	600 , 137	↓
Underaged	48	O ₂ - H ₂ O - Cl ⁻	147 , 139	
Underaged	72	N ₂ - H ₂ O - Cl ⁻	63 , 61	
Underaged ^d	72	O ₂ - H ₂ O - Cl ⁻	17 , 26	
Underaged	96	N ₂ - H ₂ O - Cl ⁻	65 , 15	
Underaged	96	O ₂ - H ₂ O - Cl ⁻	6 , 4	
Underaged	108	N ₂ - H ₂ O - Cl ⁻	23 , 87	
Underaged	108	O ₂ - H ₂ O - Cl ⁻	1.5, 1.5	
^b Overaged	0	O ₂ - H ₂ O - Cl ⁻	ⁱ	None
Overaged	0	N ₂ - H ₂ O - Cl ⁻	^j	None
Overaged	48	O ₂ - H ₂ O - Cl ⁻	2657 , 1322	None
Overaged	48	N ₂ - H ₂ O - Cl ⁻		8400, 6840
Overaged	72	O ₂ - H ₂ O - Cl ⁻	536 , 655	None
Overaged ^d	72	N ₂ - H ₂ O - Cl ⁻	2918 , 1169	↓
Overaged	96	O ₂ - H ₂ O - Cl ⁻	105 , 58	
Overaged	96	N ₂ - H ₂ O - Cl ⁻	222 , 337	
Overaged	108	O ₂ - H ₂ O - Cl ⁻	16 , 18	
Overaged	108	N ₂ - H ₂ O - Cl ⁻	56 , 76	
^c Solution Quenched	0	O ₂ - H ₂ O - Cl ⁻		None
Solution Quenched	0	N ₂ - H ₂ O - Cl ⁻		None
Solution Quenched	22.5	O ₂ - H ₂ O - Cl ⁻		5064, 5064
Solution Quenched	22.5	N ₂ - H ₂ O - Cl ⁻		5064, 5064

^aMaterial aged 6 hours at 250 °C.^bMaterial aged 80 minutes at 600 °C.^cSolution quenched condition (the soft condition).^dAll test temperatures were 26 °C ± 2.^eOxygen-saturated distilled water with 50 parts per million (ppm) chloride ions.^fNitrogen-saturated distilled water with 50 ppm chloride ions.^gBoth samples removed from environment after 1.5-hours; tensile tests indicated ultimate strengths of 144 and 149 thousand pounds per square inch (see Table IV).^hSamples removed from environment after 23 and 87 hours; tensile tests indicated ultimate strengths of 139 and 151 thousand pounds per square inch, respectively (see Table IV).ⁱSamples removed from environment after 16 and 18 hours; tensile tests indicated ultimate strengths of 158 and 158 thousand pounds per square inch, respectively (see Table IV).^jSamples removed from environment after 56 and 76 hours; tensile tests indicated ultimate strengths of 172 and 167 thousand pounds per square inch, respectively (see Table IV).^kTest times are as of 8:00 am, July 2, 1975.

TABLE IV. Characteristics of the underaged and overaged stress-corrosion cracking tests on uranium 6-weight percent niobium.

<u>A</u> Unexposed-Unstressed Tensile Tested (thousand pounds per square inch)	<u>B</u> Exposed-Unstressed Tensile Tested (thousand pounds per square inch)	<u>C</u> Exposed-Stressed Specimen Load (thousand pounds per square inch)
140 [980 megapascals (MPa)] ↓ 185 (1,295 MPa) ↓	Underaged, Oxygen (O ₂) 144 (1,008 MPa) Underaged, (O ₂) 149 (1,043 MPa) Underaged, Nitrogen (N ₂) 139 (973 MPa) Underaged, (N ₂) 151 (1,057 MPa) Overaged, (O ₂) 158 (1,106 MPa) Overaged, (O ₂) 158 (1,106 MPa) Overaged, (N ₂) 172 (1,204 MPa) Overaged, (N ₂) 167 (1,169 MPa)	108 (756 MPa) ↓

The U 6-wt % Nb alloy in the gamma-quenched condition did not show any susceptibility to stress-corrosion cracking when loaded to 90 percent of yield strength in either the oxygen-saturated or nitrogen-saturated aqueous solutions containing 50 ppm Cl⁻. The gamma-quenched material (water quenched after one hour at 850 °C) had a 0.2 percent offset yield strength of about 27,000 psi (189 MPa) and an ultimate strength of 115,000 psi (805 MPa) and was stressed to 90 percent of yield, i.e., 24,000 psi (168 MPa). Failure did not occur in 5,064 hours (211 days) of testing in either of the hostile environments. Thus, one can conclude that the gamma-quenched material is not susceptible to stress-corrosion cracking in the two chloride-ion solutions tested.

The underaged alloy in oxygen-saturated water containing 50 ppm chloride ions showed failures when stressed at 90, 80, 60, and 40 percent of yield strength, but not when stressed at 20 percent of yield. The stress required for failure was linear with respect to a log-time scale (Figure 3), and at zero time was approximately the ultimate tensile strength of the alloy. A threshold stress may exist between 24,000 and 48,000 psi (168 and 336 MPa),

since no failures were observed after 8,760 hours (365 days) of testing at 20 percent of yield strength.

The underaged alloy in nitrogen-saturated water containing 50 ppm Cl⁻ also showed failures when tested at 90, 80, 60, and 40 percent of yield strength. However, the time-to-failure varied appreciably (Figure 4) and may indicate that oxygen is required for stress-corrosion cracking in the nitrogen-saturated aqueous solutions containing 50 ppm Cl⁻. The time-to-failure would then include the time required for the necessary oxygen to get into the environmental chamber. None-the-less, one can conclude that the underaged material stress-corrosion cracks in both environments and that the susceptibility is greater in oxygen-saturated rather than nitrogen-saturated aqueous chloride solutions (Figure 7).

The underaged alloys (6 hours at 250 °C) showed a mixed transgranular and intergranular fracture mode in both environments with the transgranular mode predominating. Figures 8(a) and (b) show transverse views of the fracture zone of a sample tested at 80 percent of yield strength in the oxygen-saturated aqueous chloride solution.

FIGURE 3. Stress-corrosion cracking behavior of underaged (6 hours at 250 °C) uranium 6-weight percent niobium in oxygen-saturated water containing 50 parts per million chloride ions.

FIGURE 4. Stress-corrosion cracking behavior of underaged (6 hours at 250 °C) uranium 6-weight percent niobium in nitrogen-saturated water containing 50 parts per million chloride ions.

FIGURE 5. Stress-corrosion cracking behavior of overaged (80 minutes at 600 °C) uranium 6-weight percent niobium in oxygen-saturated water containing 50 parts per million chloride ions.

FIGURE 6. Stress-corrosion cracking behavior of overaged (80 minutes at 600 °C) uranium 6-weight percent niobium in nitrogen-saturated water containing 50 parts per million chloride ions.

FIGURE 7. Comparative stress-corrosion cracking behavior of the solution-quenched, underaged, and overaged uranium 6-weight percent niobium alloy in oxygen and nitrogen saturated water containing 50 parts per million chloride ions.

FIGURES 8(a) and (b). Transverse views of fracture zone of underaged uranium 6-weight percent niobium alloy tested at 80 percent of yield strength in oxygen-saturated water containing 50 parts per million chloride ions. Magnification 200X.

Figures 9(a) and (b) show transverse views after testing at 90 percent of yield in the nitrogen-saturated aqueous chloride solution. The fracture mode for underaged samples tested in air was transgranular. Hence, the two test environments do promote intergranular cracking.

The overaged alloy (80 minutes at 600 °C) in oxygen-saturated aqueous chloride solution showed

failures when tested at 90, 80, 60, and 40 percent of yield strength (120 ksi or 840 MPa). As with the underaged alloy, the stress required for failure was linear with respect to a log-time scale (Figure 5), and when extrapolated to zero time was approximately the ultimate tensile strength of the alloy. The time required for failure was significantly longer than that of the underaged material under similar conditions of stress and

FIGURES 9(a) and (b). Transverse views of fracture zone of underaged uranium 6-weight percent niobium alloy tested at 90 percent of yield strength in nitrogen-saturated water containing 50 parts per million chloride ions.

environment. Thus, one can conclude that the overaged alloy is less susceptible to stress-corrosion cracking than is the underaged alloy. However, this may be due to a higher ultimate tensile strength in the overaged material, even though both had approximately the same 0.2-percent offset yield strengths.

The overaged alloy in nitrogen-saturated water containing 50 ppm Cl^- also showed failures when tested at 90, 80, and 60 percent of yield strength, but not when tested at 40 percent of yield strength (Figure 6). This, however, does not indicate a threshold value, but merely that the samples were not stressed long enough for failure to occur.

An extrapolation of the fracture data would indicate a life of about 20,000 hours (833 days), and the samples were only tested for 8,400 hours (350 days). The overaged alloy in the N_2 - H_2O - Cl^- solution had the longest time-to-failure of the four overaged and underaged alloys tested. Here again, this may be due to the higher ultimate tensile strength of the overaged material and the necessity for oxygen leakage into the N_2 - H_2O - Cl^- solution in the environmental chamber.

In view of the earlier statement, the question arises as to why samples were not tested in oxygen-saturated distilled water without chloride ions, i.e., oxygen may be a more important ingredient than chloride ions. The reason related to an earlier effort which showed (19) that SCC specimens of the U 4.2-wt % Nb alloy had extremely long lives in oxygen-saturated distilled water, and that chloride ions were required for, or at least accelerated, the nucleation or propagation (or both) of SCC cracks. For comparison, the time-to-failure of the U 4.2-wt % Nb underaged (80 hours at 260 °C) alloy in oxygen-saturated distilled water containing 50 ppm chloride ion is shown in Figure 7. Thus, the U 6-wt % Nb alloy is much less susceptible to stress corrosion cracking in O_2 - H_2O - Cl^- solutions than is the U 4.2-wt % Nb alloy.

It has been stated, especially with constant load tests, that the stress-corrosion of an alloy with unknown susceptibility can be established by exposing both stressed and unstressed specimens to the same corrosive environment (23). For instance, three tension specimens, A, B, and C, are used as examples. Specimen A is an unexposed, unstressed blank; Specimen B is exposed to a corrosive environment, but in an unstressed condition. Specimen C is both stressed and exposed to the same corrosive environment. When Specimen C breaks, under the combined influence of stress and corrosion, Specimen B is tension-tested. If Specimen B has a breaking load closer to that of Specimen A, the evidence is greater that Specimen C failed at a result of stress-corrosion cracking. This appears to be the case with the underaged material as shown in Table IV and in Figures 3 and 4.

If, however, the breaking load of Specimen B is closer to the load on Specimen C, then the failure

of Specimen C should not be attributed to stress-corrosion cracking, but rather to the probability that the specimen corroded to the point where it could no longer support the load. The breaking load of the overaged B specimens (exposed but unstressed) is somewhat closer to the overaged A specimens (unexposed and unstressed). Nonetheless, the overaged B specimens had a reduced breaking load when compared to the overaged A specimens (Table IV and Figures 5 and 6), and do indicate that corrosion reduced the effective cross-sectional area of these specimens resulting in an overload condition and a partial mechanical failure. Also, visual examination showed that corrosion effectively reduced the cross-sectional area of these specimens. Therefore, the overaged material partially fails by corrosion reducing the cross-sectional area rather than totally by an SCC fracture mode.

The structure of the overaged material (80 minutes at 600 °C) is fine pearlite consisting of orthorhombic alpha and body-centered-cubic gamma phase. Optical micrographs did not clearly resolve the fine pearlite, but prior gamma grain boundaries are discernible (Figure 10). Replicas of the surface in an electron microscope did resolve the fine pearlite (Figure 11). Due to the nature of the microstructure, the fracture mode would have to be, at least, partially transcrystalline. However because of the fineness of the structure, this was not actually observed. A macroscopic view of the fracture is shown in Figure 12. The smooth area near the initiation of the overload fracture is probably a stress-corrosion crack which acted as a stress raiser causing the overload fracture.

CONCLUSIONS

1. The U 6-wt % Nb alloy in the solution-quenched condition does not appear to be susceptible to stress-corrosion cracking when loaded to 90 percent of yield strength in oxygen or nitrogen saturated solutions containing 50 ppm chloride ions.
2. The U 6-wt % Nb alloy in the underaged condition (6 hours at 250 °C) is susceptible

FIGURE 10. Optical photomicrograph of uranium 6-weight percent niobium alloy aged 80 minutes at 600 °C showing partially resolved pearlitic structure within prior gamma grain boundaries. Magnification 1000X.

FIGURE 11. Electron micrograph of replicated surface of sample in Figure 10 showing resolved pearlitic structure. Magnification 5000X.

FIGURE 12. Macroscopic view of fracture surface of overaged uranium 6-weight percent niobium alloy tested at 60 percent of yield strength in nitrogen-saturated water containing 50 parts per million chloride ions. Magnification 12X.

to stress-corrosion cracking in oxygen-saturated solutions containing 50 ppm chloride ions when loaded at 90, 80, 60, and 40 percent of yield strength, but not when loaded at 20 percent of yield indicating a threshold value.

3. The underaged alloy is also susceptible to SCC in nitrogen-saturated aqueous chloride solutions when loaded at 90, 80, 60, and 40 percent of yield strength.
4. The U 6-wt % Nb alloy in the overaged conditions (80 minutes at 600 °C) also fails when loaded to 90, 80, 60, and 40 percent of yield strength in either oxygen or nitrogen saturated aqueous solutions containing 50 ppm chloride ions. Both a mechanical cracking mode and a stress-corrosion cracking mode appear to be operable, i.e., stress-corrosion cracks form at the same time corrosion is reducing the cross-sectional area of the material.
5. The order of susceptibility to stress-corrosion cracking of the U 6-wt % Nb alloy is:
 - a. Most susceptible - Underaged alloy in O_2 - H_2O - Cl^- environment.
 - b. Most susceptible - Underaged alloy in N_2 - H_2O - Cl^- environment.
 - c. Most susceptible - Overaged alloy in O_2 - H_2O - Cl^- environment.
 - d. Most susceptible - Overaged alloy in N_2 - H_2O - Cl^- environment.
 - e. Least susceptible - Solution-quenched alloy in either the O_2 - H_2O - Cl^- or N_2 - H_2O - Cl^- environments.

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