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INFLUENCE OF A FLOWING-LITHIUM ENVIRONMENT ON THE FATIGUE AND TENSILE PROPERTIES OF TYPE 316 STAINLESS STEEL*

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INFLUENCE OF A FLOWING LITHIUM ENVIRONMENT ON THE FATIGUE AND TENSILE PROPERTIES OF TYPE 316 STAINLESS STEEL

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Low-cycle fatigue and tensile data have been obtained on Type 316 stainless steel in a flowing lithium environment of controlled purity. The results show that the fatigue life of the steel in flowing lithium at 755 K is greater than in air. Preexposure of the material to lithium reduces fatigue life. The reduction in fatigue life may be attributed to the formation of a weak ferrite layer after lithium exposure. Tensile data for cold-worked Type 316 stainless steel indicate that at temperatures between 476 and 755 K, a flowing lithium environment has little or no effect on the tensile properties of the steel.

1. INTRODUCTION

Liquid lithium has been proposed as the tritium breeder and/or as a coolant in several design concepts for fusion reactors. The use of liquid lithium for such applications requires an assessment of the environmental effects on the mechanical properties of structural alloys. Liquid metal environments can influence processes at a free surface and change the surface-active properties of the material. The compositional and microstructural changes that occur in the material during long exposures to the environment may change its bulk properties. Furthermore, the cyclic plasma burn projected for some reactor concepts will induce severe cyclic thermal stresses in the first-wall/blanket structure. Consequently, the fatigue behavior of the material is an important consideration in the design of the first-wall/blanket region.

Studies on the mechanical behavior of materials in a liquid lithium environment indicate that the environment itself may cause degradation of mechanical properties of ferrous alloys.[1,2] Low-cycle fatigue data in a flowing lithium environment at 755 K (482°C) show that the most important parameter in controlling the fatigue properties is the concentration of nitrogen in lithium.[3,4] The fatigue life of HT-9 alloy and Type 304 stainless steel in lithium containing <200 ppm nitrogen is greater than that in air. However, the fatigue life of the HT-9 alloy in lithium with 1000-1500 ppm nitrogen is a factor of 2 to 5 lower than in low-nitrogen lithium. The reduction in fatigue life in high-nitrogen lithium is attributed to intergranular corrosion of the material.

Data for the effect of lithium on the tensile properties of materials indicate that at temperatures between 473 and 1073 K (200 and 800°C), the tensile strength and, most particularly, the ductility of Armco iron in lithium are considerably lower than in vacuum.[5] The tensile strength of Fe-17Cr-10Ni (wt %) stainless steel is not significantly affected by lithium;[6] however, the ductility depends on strain rate and temperature. Enhanced fatigue crack propagation rates (da/dN) in a lithium environment have been

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observed for Fe-2 1/4Cr-1Mo ferritic steel and Type 304L stainless steel at temperatures between 473 and 773 K (200 and 500°C).[7-10] The higher crack growth rates have been attributed to corrosion at high temperatures and to strain-rate-induced, liquid metal embrittlement at low temperatures.

The objective of this investigation is to evaluate the effects of a flowing lithium environment on the fatigue and tensile properties of Type 316 stainless steel. Low-cycle fatigue data are presented on solution-annealed and lithium-exposed material tested in lithium at 755 K (482°C). The tensile properties of 20% cold-worked Type 316 stainless steel in flowing lithium at temperatures between 476 and 755 K (203 and 482°C) are compared with results in vacuum.

2. SPECIMENS AND EXPERIMENTAL PROCEDURES

The mechanical tests were conducted in a forced-circulation lithium loop equipped with three test vessels and a cold-trap purification system to control the concentration of nonmetallic elements, e.g., N, C, and H. The cold-trap temperature was maintained at 498 K (225°C). Hot trapping with Ti or Zr foils was used to reduce the nitrogen level to <200 ppm in lithium. During the tests, the concentration of carbon and hydrogen in lithium was ~8 and 120 ppm, respectively. Lithium within the test vessel was circulated at a flow rate of ~1 liter/min.

Tests in flowing lithium were conducted with an MTS closed-loop servohydraulic machine. The fatigue tests were performed on uniform-gauge specimens in the axial stroke-control mode, with a fully reversed triangular waveform and a strain rate of ~4×10^{-3} s^{-1}. The details of the fatigue test facility and the procedure for strain control and strain measurement have been described earlier.[4] The tensile tests were conducted on flat specimens at an initial strain rate of ~4×10^{-4} s^{-1}. An Instron machine was used for the tests in vacuum.

The fatigue test specimens, with a 5.08-mm diameter and 12.7-mm gauge length, were fabricated from 16-mm-diameter rods of Type 316 stainless steel that had been solution annealed for 1.8 ks in argon at 1298 K (1025°C) and water quenched. Some specimens were preexposed to flowing lithium at 755 K prior to fatigue testing. Tensile specimens were fabricated from 1.27-mm-thick flat stock that was 20% cold worked by rolling. The specimens had a gauge length of 22.2 mm and a width of 5.59 mm.

3. RESULTS

3.1 Fatigue tests

The relationship between total strain range and fatigue life for solution-annealed and lithium-preexposed Type 316 stainless steel in flowing lithium at 755 K (482°C) is shown in Fig. 1. Data for solution-annealed Type 316 stainless steel in air at 755 K[11] and in flowing sodium at 823 K[12] are also included in Fig. 1 for comparison. The results show that the fatigue life in low-nitrogen lithium is a factor of 3 to 8 greater than in air and ~25% greater than in sodium. The increased fatigue life in lithium is consistent with the data on the fatigue behavior of the HT-9 alloy and Type 304L stainless steel in lithium. The difference in fatigue life in air and lithium environments is attributed to the absence of oxidation effects in lithium.

The influence of lithium exposure on the fatigue life of Type 316 stainless steel was investigated by conducting tests on specimens that were preexposed at 755 K for 4.7 Ms (1300 h) in flowing lithium containing <200 ppm nitrogen. One specimen was exposed

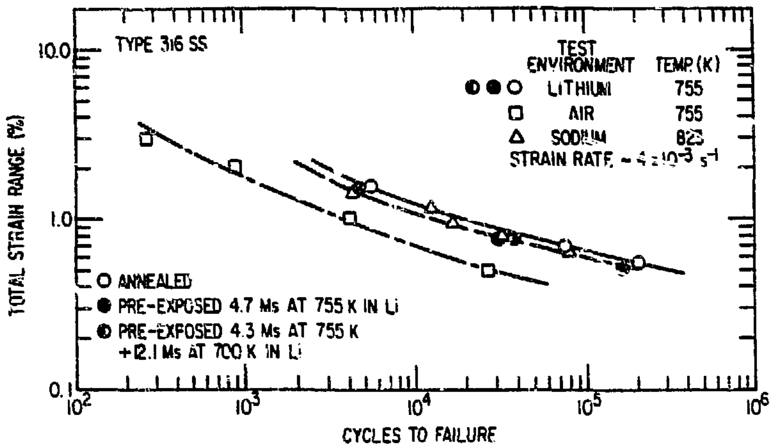

FIGURE 1

Total strain range vs cycles to failure for solution-annealed and lithium-preexposed Type 316 stainless steel tested in air and flowing lithium and sodium environments. Data in air and sodium from Refs. 11 and 12, respectively.

for an additional 12.1 Ms (3350 h) at 700 K (427°C) after the exposure at 755 K. The results indicate that preexposure of the steel to lithium decreases fatigue life relative to the fatigue life of the solution-annealed steel. The fatigue life of the specimens exposed for 4.7 Ms at 755 K is ~25% lower and that of the specimen exposed for an additional time at 700 K is ~50% lower than that of the solution-annealed steel.

The test specimens were examined metallographically to evaluate the influence of the lithium environment on the mode of fracture and surface markings on the gauge section. Micrographs of the gauge surfaces of annealed and preexposed specimens tested in lithium are shown in Fig. 2. Both specimens show an etched or a pebbled surface, which is typical of ferrous alloys exposed to lithium. The preexposed specimen shows greater corrosion and contains several circumferential cracks. Examination of the cross section of the lithium-preexposed specimens revealed a 30 to 40-μm-thick porous ferrite layer at the surface.

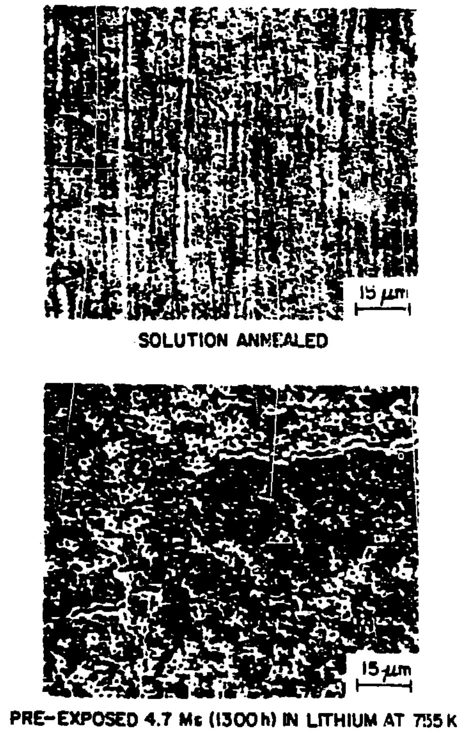

FIGURE 2

Micrographs of the gauge surfaces of solution-annealed and preexposed Type 316 stainless steel tested in lithium at 755 K

It is well known that austenitic stainless steels develop a ferrite layer after exposure to lithium owing to preferential depletion of nickel, and to a lesser extent chromium, from the steel.[2] The weak ferrite layer probably leads to early crack initiation and thereby reduces fatigue life. The fracture surface of the lithium-preexposed specimen tested in lithium is shown in Fig. 3. The micrograph shows a typical fatigue fracture surface with very diffuse striations and a porous ferrite layer at the surface.

3.2 Tensile tests

The influence of a lithium environment on the tensile properties of 20% cold-worked Type 316 stainless steel was investigated from tensile tests in flowing lithium and in vacuum at temperatures between 476 and 755 K (203 and 482°C). Figure 4 shows the ultimate and tensile strength and total elongation of the material in lithium and vacuum. The curves in Fig. 4 represent the average values for 20% cold-worked Type 316 stainless steel in air. The results show that a lithium environment has little or no effect on the tensile properties of the steel. Although the tests in lithium at temperatures below 644 K (371°C) show a slight increase in yield strength and a decrease in ultimate strength, the total elongations of the material in lithium and vacuum are comparable.

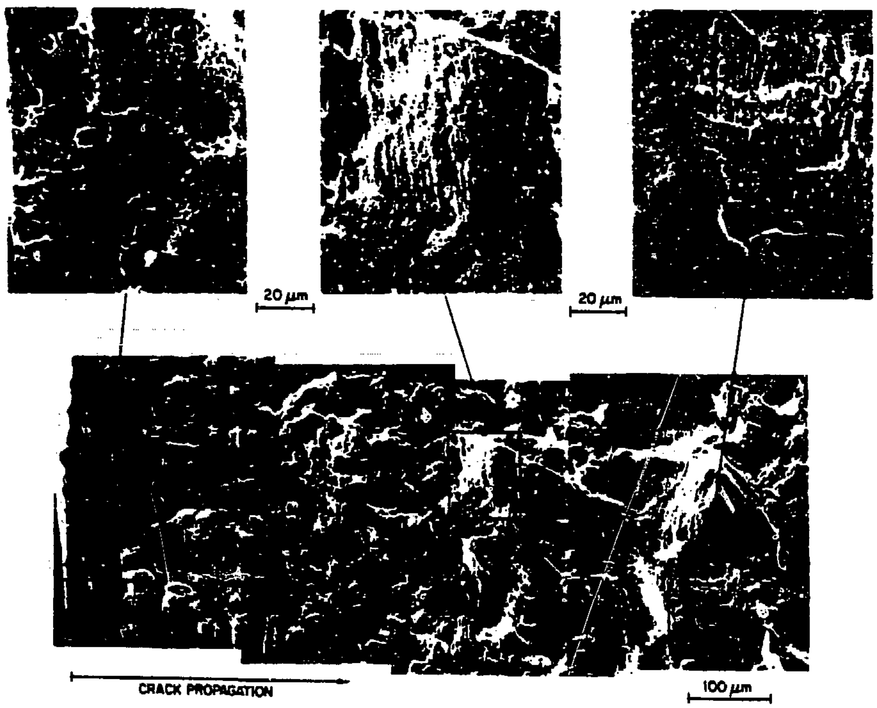

FIGURE 3
Micrographs of the fracture surface of lithium-preexposed Type 316 stainless steel tested in lithium at 755 K

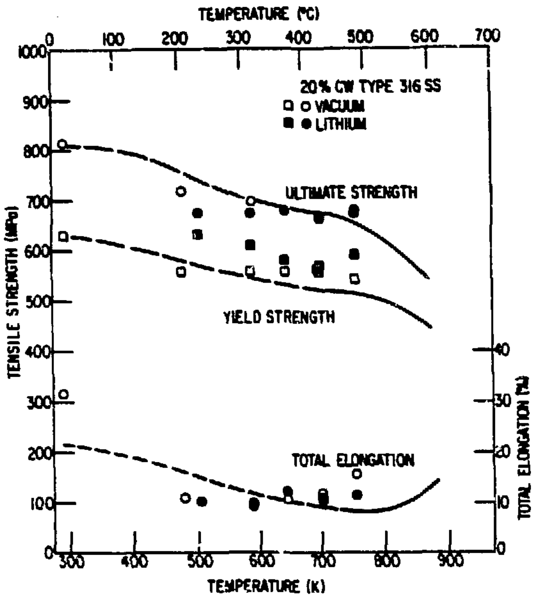

FIGURE 4
Ultimate and yield strength and total elongation of 20% cold-worked Type 316 stainless steel tested in flowing lithium or vacuum. The curves represent the average values in air.

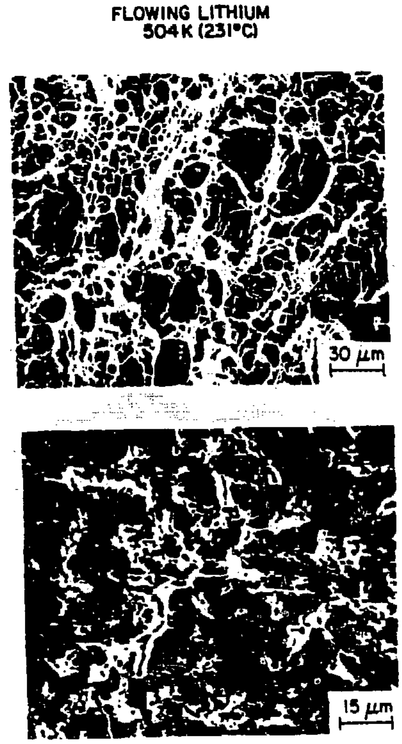

FIGURE 5
Micrographs of the fracture surface (top) and gauge surface (bottom) of 20% cold-worked Type 316 stainless steel specimens tested in lithium at 504 K

For all test temperatures, the specimens showed a dimpled ductile fracture in both environments. The gauge surfaces also exhibited identical features. Micrographs of the fracture surface and gauge surface of specimens tested in lithium at 504 K are shown in Fig. 5. Surface cracks, perpendicular to the stress axis, were observed in both lithium and vacuum. However, examination of the longitudinal sections of the specimens revealed that these surface cracks do not extend into the bulk material.

4. DISCUSSION AND CONCLUSIONS

Fatigue data in flowing lithium at 755 K indicate that the environment per se has no deleterious effects on the fatigue properties of Type 316 stainless steel. The fatigue life in low-nitrogen lithium is a factor of 3 to 8 greater than in air. The superior fatigue life in lithium may be attributed to the absence of oxidation effects. Failure under fatigue straining occurs by initiation of a crack at the free surface and transgranular propagation of the crack to complete failure. Environmental effects, such as oxidation or corrosion, may affect both crack initiation and propagation. The fracture and gauge surfaces of the specimens tested in lithium are virtually free of any surface oxide. On the other hand, specimens tested in air at elevated temperatures show thin surface oxides that may influence fatigue deformation in several ways. For example, oxidation of the slip steps or adsorption of nonmetallic elements at slip bands can prevent slip reversal and accelerate cracking. Strengthening of the surface due to the oxide film can cause strain accumulation and enhanced cavitation. Such phenomena can decrease the period of crack initiation and increase crack propagation rates and, therefore, reduce the continuous-cycle fatigue life in air. Data from fatigue crack propagation studies indicate that a lithium environment increases the fatigue crack propagation rates (da/dN) for Type 304L stainless steel and Fe-2 1/4Cr-1Mo steel relative to that in argon.[9,10] However, the results were not compared with crack propagation rates in air.

Results for the lithium-exposed specimens indicate that preexposure of Type 316 stainless steel to lithium decreases its fatigue life. Metallographic examination of the lithium-preexposed specimens revealed a porous ferrite layer and several secondary cracks at the surface. The presence of a weak surface layer may facilitate crack initiation and thus cause a reduction in fatigue life. The crack propagation behavior is not significantly influenced by lithium preexposure; the fracture mode of the lithium-preexposed steel is similar to that of the solution-annealed material. However, for the present study, lithium preexposure was carried out for relatively short times. Additional data on lithium-exposed steel are required to establish the long-term environmental effects on the fatigue properties of Type 316 stainless steel.

Tensile data for cold-worked Type 316 stainless steel indicate that a flowing lithium environment has little or no effect on the tensile strength or total elongation of the steel. The tensile properties in flowing lithium at temperatures between 476 and 755 K and a strain rate of ~4 x 10^{-4} s^{-1} are comparable to those in vacuum. Tensile tests at strain rates of 4 x 10^{-2} and 4 x 10^{-6} s^{-1} are needed to investigate the influence of corrosion and the possible embrittlement of the steel at other strain rates.

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