EFFECTS OF SODIUM ENVIRONMENT ON THE MECHANICAL PROPERTIES OF Fe-2 1/4Cr-1Mo STEEL

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ABSTRACT

Mechanical property data on isothermally annealed, thermally aged, and sodium-exposed Fe-2 1/4Cr-1Mo steel are analyzed to evaluate the influence of the sodium environment as well as the effects of the microstructural and compositional changes that occur in the steel during long-term exposure to sodium. Correlations are developed to predict the environmental effects on tensile, creep, fatigue, and creep-fatigue properties of Fe-2 1/4Cr-1Mo steel in sodium. The results indicate that at temperatures <823 K (550°C), degradation of mechanical properties is essentially due to thermal aging. Loss of carbon from the steel reduces both the tensile and creep-rupture strength, but has little or no effect on the fatigue properties. The cyclic properties of Fe-2 1/4Cr-1Mo steel in sodium are superior to those in air. The creep-fatigue behavior in sodium is significantly different from that in an air environment. The creep-fatigue data are analyzed using the interactive damage rate equations to predict the time-dependent fatigue behavior of isothermally annealed Fe-2 1/4Cr-1Mo steel in sodium.

INTRODUCTION

Low-alloy Fe-2 1/4Cr-1Mo ferritic steel is commonly used in the construction of sodium-heated steam evaporator and superheater units for liquid-metal fast breeder reactors. A major concern for such application is the susceptibility of the steel to decarburization when exposed to high-temperature flowing sodium.[1-4] Carbon is known to migrate in liquid sodium heat-transport systems as a result of carbon activity gradients produced by both temperature and compositional differences. The Fe-2 1/4Cr-1Mo steel decarburizes because of its inherently high carbon activity and large carbon diffusion coefficient. The loss of carbon from the material may lead to significant reduction in elevated-temperature mechanical strength. Furthermore, liquid sodium can influence the surface-active properties of the material depending on the purity of the environment, i.e., the chemical activity of oxygen, nitrogen, carbon, etc. in the sodium. The chemical activity of oxygen in liquid sodium is much lower than that in other test environments, such as air and steam. Therefore, oxidation of the material will not influence mechanical properties in liquid sodium.

The objective of this paper is to establish quantitatively the effects of the low-oxygen environment and decarburization during long-term sodium exposure on the mechanical properties of isothermally annealed Fe-2 1/4Cr-1Mo steel. Data obtained on annealed, thermally aged, and sodium-exposed material are analyzed to evaluate the environmental effects on tensile, creep, fatigue, and creep-fatigue properties.

Tensile and Creep Properties

The long-term effects of sodium exposure on the tensile and creep properties of Fe-2 1/4Cr-1Mo steel have been investigated by testing sodium-exposed material in an inert or air environment. When exposed to high-temperature sodium, the Fe-2 1/4Cr-1Mo steel undergoes decarburization, as well as compositional and microstructural changes due to thermal aging. Data on the tensile and creep properties of sodium-exposed Fe-2 1/4Cr-1Mo steel indicate that loss of carbon and thermal aging can independently reduce mechanical strength.[5-11] Consequently, the effects of thermal aging per se on tensile and creep properties have to be evaluated to assess the influence of carbon loss. Sodium exposure of Fe-2 1/4Cr-1Mo steel leads to carbon concentration profiles rather than uniform distribution of carbon in the material. For components with intermediate section thicknesses, e.g., pipe, the decrease in strength is proportional to the depth of the decarburized layer. Maximum reduction in strength will occur in thin-walled components, namely, superheater and evaporator tubing. Ideally, the long-term effects of sodium should be established from data on material in which the decarburized layer extends to specific depths, which were established under known conditions of time, temperature, and sodium purity. Such an approach, however, is complex and impractical. The current assessment of the change in mechanical strength of Fe-2 1/4Cr-1Mo steel due to decarburization in sodium is primarily based on data obtained from steels that were decarburized to different average carbon concentrations. Often the results from steels with low initial bulk carbon contents are included in the analysis to supplement the data from decarburized material.

Figure 1 shows the influence of carbon loss on the ultimate and yield strength of decarburized Fe-2 1/4Cr-1Mo steel. The reduction in tensile strength is expressed as the ratio of the actual tensile strength of the specimens and the strength predicted for material after thermal aging for identical time and temperature. Tensile data were obtained at 783 K (510°C) on isothermally annealed material that was given a postweld heat treatment (PWHT). Sodium exposure was carried out in both static and flowing sodium at temperatures between 797 and 1000 K (524 and 727°C). The maximum temperature of 1000 K was selected to accelerate the kinetics of carbon transfer and achieve low concentrations of carbon in the material. The minimum temperature of 797 K was selected to match the maximum design temperature for the intermediate heat transfer loop in the Clinch River Breeder Reactor (CRBR). Sodium exposures ranged from 1.8 Ms (500 h) at 1000 K to 82.8 Ms (23,000 h) at 797 K. Thermal aging was carried out in an inert environment for time and temperature conditions identical to those for the sodium-exposed material. The data were normalized in terms of a time-temperature parameter to predict the reduction in tensile strength due to thermal aging. The results indicate that a carbon loss of ~0.04 wt % during the design life of superheater tubing (~3 mm thick) would result in an ~5% reduction in ultimate strength and an ~3% reduction in yield strength. The reduction in tensile strength due to thermal aging is significantly greater than that from decarburization.

Creep rupture data at temperatures between 755 and 866 K (482 and 593°C) indicate that the influence of thermal aging is predominant at temperatures <773 K, whereas decarburization has a substantial effect at higher temperatures.[6,9] At 866 K, the thermal aging processes are relatively fast and occur during the test; consequently, differences in the creep rupture behavior for

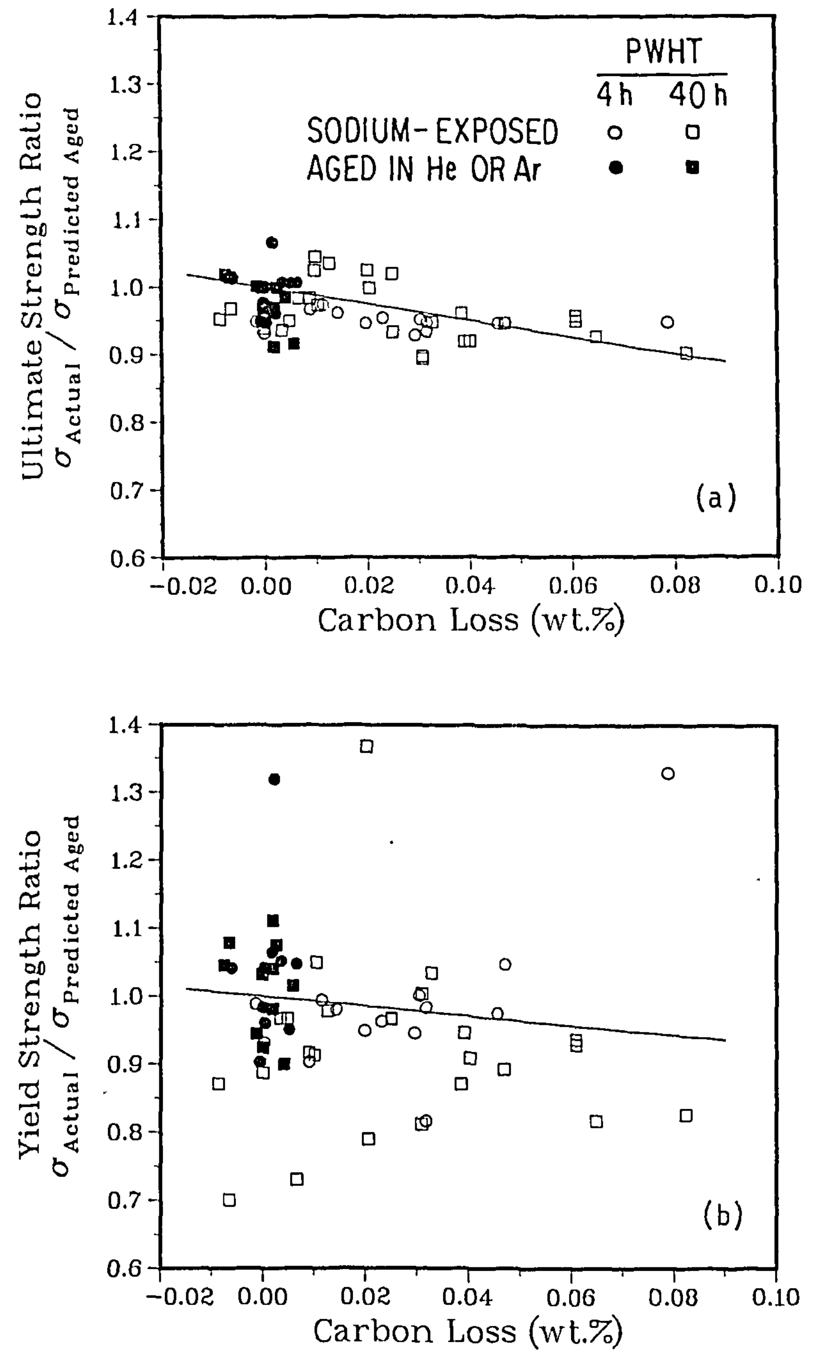

Fig. 1. Effect of Carbon Loss on the (a) Ultimate and (b) Yield Strength of Fe-2 1/4Cr-1Mo Steel (Refs. 5 and 6).

thermally aged and isothermally annealed material are not significant. However, the steel undergoes significant decarburization when exposed to sodium at 866 K. The loss of carbon and the associated changes in carbide morphology result in degradation of the creep rupture strength. At lower temperatures, the kinetics of the decarburization and thermal aging processes are slow; consequently, the difference between the rupture strength for annealed and thermally aged or sodium-exposed steel is primarily due to thermal aging.

The reduction in creep rupture strength due to decarburization can be assessed from data on steels with low initial carbon contents.[12] The predicted reduction in rupture strength due to carbon loss in a sodium environment is shown in Fig. 2. The creep rupture strength ratio (corrected for thermal aging effects) for material that was decarburized in sodium to different bulk carbon contents is also plotted in Fig. 2 and shows a good agreement with the predicted curve. The analysis indicates that the reduction in creep rupture strength for Fe-2 1/4Cr-1Mo steel superheater tubing during a service life at 783 K will be ~12%.

Fatigue and Creep-Fatigue Properties

In contrast to the tensile and creep properties, where the variation in mechanical strength is primarily due to decarburization/carburization or thermal aging rather than the sodium environment per se, the fatigue behavior of Fe-2 1/4Cr-1Mo steel in sodium is superior to that in air.[12,13] Failure under fatigue straining occurs by initiation of a crack at the free surface and transgranular propagation of the crack to complete fracture. Environmental effects, such as corrosion or oxidation, may affect both the crack initiation and propagation processes. Metallographic evaluation of the fracture surface and the liquid/alloy interface in the gauge region of the specimens tested in sodium indicates that environmental effects are virtually absent in a low-oxygen sodium environment. Specimens are absolutely free of oxides or any other corrosion product. On the other hand, fatigue tests conducted in air at high temperatures show substantial oxidation, which influences the cyclic deformation behavior of the material and reduces the fatigue life relative to that in sodium.

The fatigue strain-life relationships for Fe-2 1/4Cr-1Mo steel in the isothermally annealed and the thermally aged or sodium-exposed conditions are shown in Figs. 3 and 4, respectively. The results show that at temperatures between 755 and 866 K, the fatigue life in sodium is a factor of 2 to 8 greater than in air; the difference is larger at 866 K. The fatigue life of thermally aged and sodium-exposed material is 30-50% lower than that of the isothermally annealed steel. The decrease in fatigue life for the sodium-exposed steel is primarily due to thermal aging and the loss of carbon has little or no effect on fatigue life. For example, the fatigue life of sodium-exposed specimens containing 0.07-0.11 wt % carbon is identical with that of the thermally aged specimens with 0.12 wt % carbon.

Fatigue data in sodium also show that the plastic strain-life behavior of Fe-2 1/4Cr-1Mo steel is independent of temperature and strain rate. The total strain-life relationship shows a slight variation with temperature and strain rate because of the difference in the cyclic stress-strain response. The

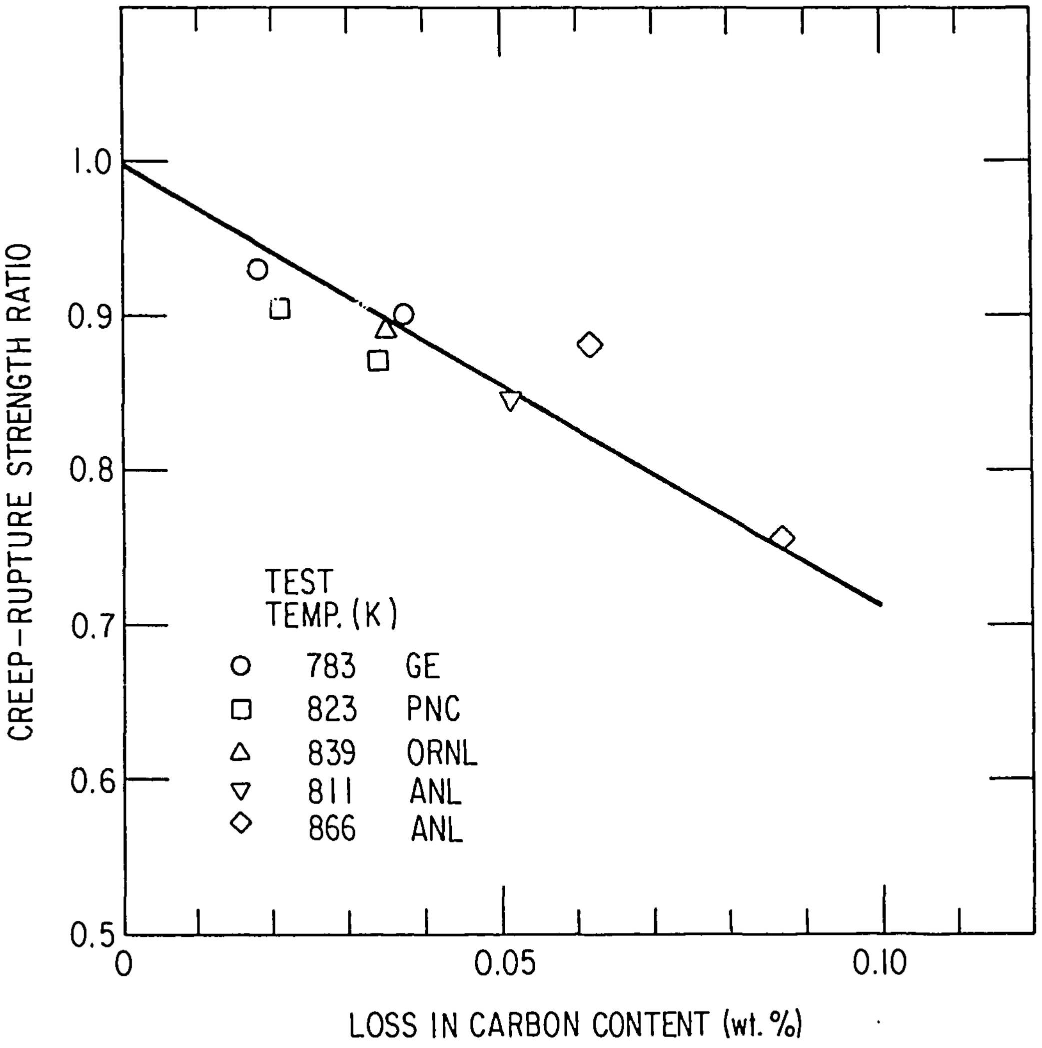

Fig. 2. Relation Between Loss of Carbon Due to Decarburization in Sodium and Creep Rupture Strength Ratio for Fe-2 1/4Cr-1Mo Steel. GE - General Electric (Ref. 6), PNC - Power Reactor and Nuclear Fuel Corporation, Japan (Ref. 8), ORNL - Oak Ridge National Laboratory (Ref. 10), and ANL - Argonne National Laboratory (Ref. 9).

strain-life behavior for isothermally annealed steel tested in sodium at 811 K at different strain rates is shown in Fig. 5. This behavior is different from that observed in an air environment. In air, the fatigue life of Fe-2 1/4Cr-1Mo steel decreases with a decrease in strain rate or an increase in temperature. The difference between the results in sodium and air environments can be attributed to oxidation of the material in air.

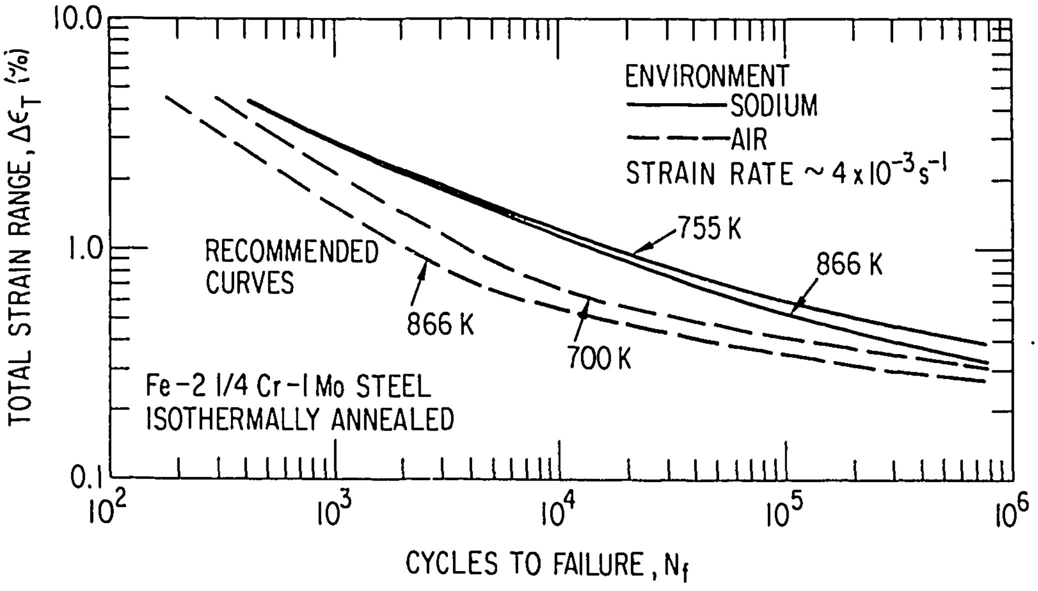

Fig. 3. Total Strain Range vs Cycles to Failure for Isothermally Annealed Fe-2 1/4Cr-1Mo Steel in Sodium and Air Environments (Ref. 13).

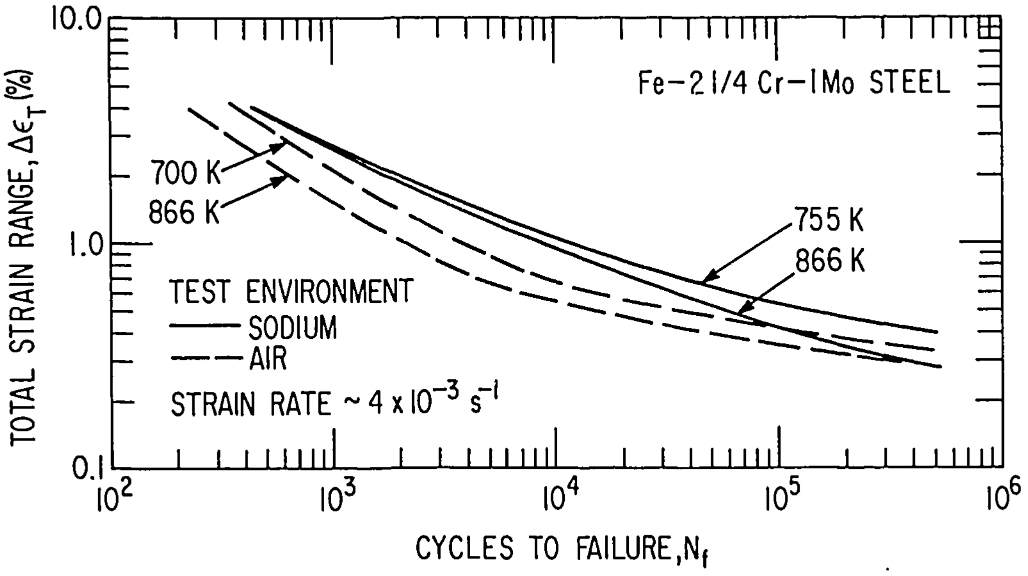

Fig. 4. Total Strain Range vs Cycles to Failure for Thermally Aged and Sodium-exposed Fe-2 1/4Cr-1Mo Steel in Sodium and Air Environments (Ref. 13).

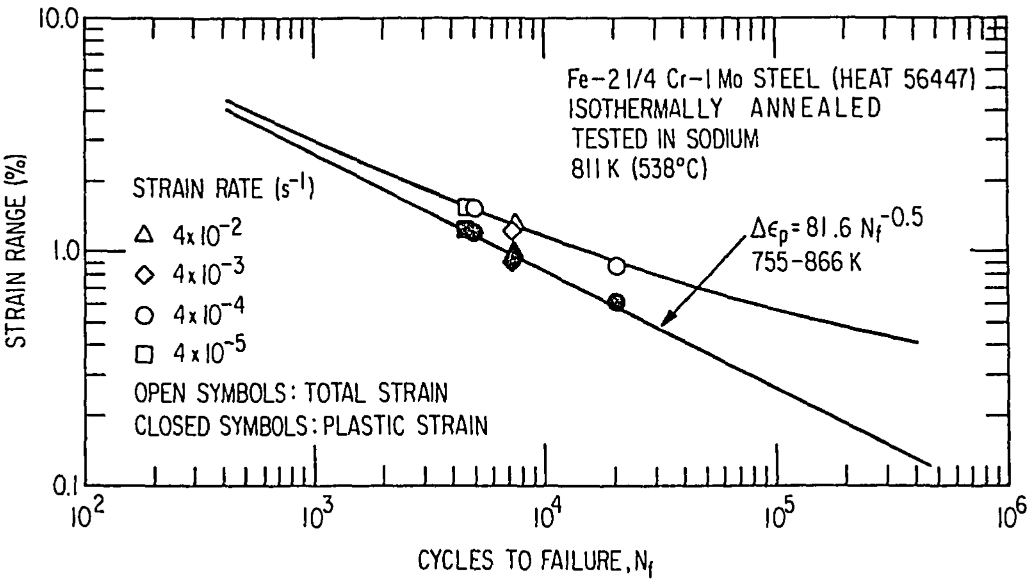

Fig. 5. Effect of Strain Rate on the Fatigue Life of Isothermally Annealed Fe-2 1/4Cr-1Mo Steel Tested in Sodium at 811 K.

The creep-fatigue behavior of Fe-2 1/4Cr-1Mo steel, determined from slow-fast, fast-slow, and tensile-hold-time tests in sodium, is shown in Fig. 6. The results reveal that the fast-slow strain sequence has no effect on the fatigue life, whereas the fatigue life for the slow-fast or tensile-hold-time tests is lower than that for the constant strain rate tests. Furthermore, the decrease in fatigue life for slow-fast tests is strongly dependent on the test temperature. For example, the fatigue life is a factor of ~4 lower for slow-fast versus constant strain rate tests at 866 K and a factor of ~2 lower at 811 K; at 755 K, the strain rate sequence has little effect on fatigue life. These results indicate that in a sodium environment, a tensile-hold period (which is similar to a slow-fast strain sequence) leads to a reduction in fatigue life, whereas a compressive-hold period (which is similar to a fast-slow strain sequence) has little or no effect. This behavior is quite different from creep-fatigue results obtained in air; e.g., at strain ranges of <1% a compressive hold period is found to be more damaging than a tensile-hold period.[14]

Metallographic examination of specimens tested in sodium with a slow-fast strain sequence or a tensile-hold period revealed surface grain boundary cracks, several secondary propagating cracks, and grain boundary cavities in the bulk.[12,13] The fracture surface shows no fatigue striations and resembles that observed for creep tests. Bulk cavitation or surface grain boundary cracks are not observed for all the constant strain rate or fast-slow tests. In this regard, it is interesting to note that the slow-fast strain sequence (i.e., tensile $\dot{\varepsilon}_t$ ~4 x 10^{-5} s^{-1} and compressive $\dot{\varepsilon}_t$ ~4 x 10^{-3} s^{-1}) leads to creep damage and reduction in fatigue life, whereas the slow-slow test at a constant strain rate of ~4 x 10^{-5} s^{-1} has no effect on fatigue life. These results indicate that internal bulk damage in low-alloy Fe-2 1/4Cr-1Mo steel occurs only during tensile creep conditions. For symmetrical hold periods or

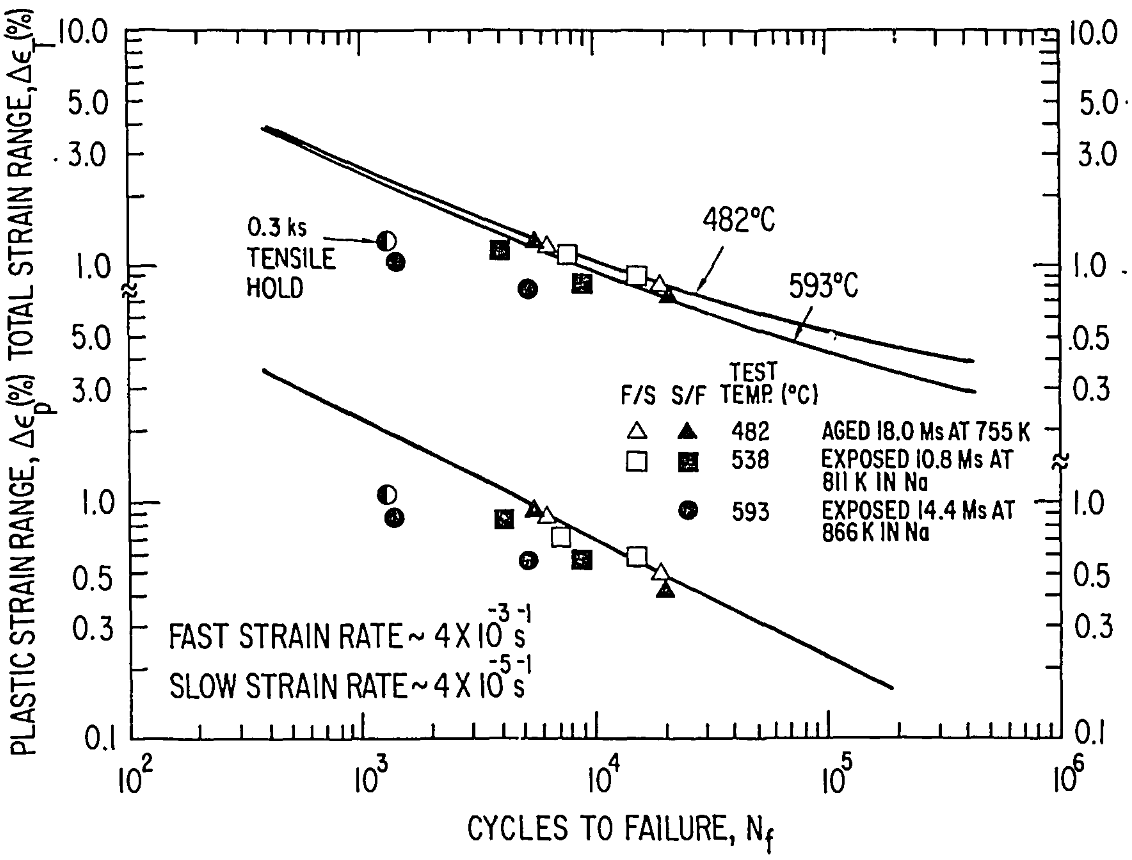

Fig. 6. Total and Plastic Strain Range vs Cycles to Failure for Thermally Aged and Sodium-exposed Fe-2 1/4Cr-1Mo Steel Tested in Sodium Using a Sawtooth Waveform.

slow-slow tests, the cavities that form during the tensile half of the fatigue cycle either anneal out during the compressive cycle or do not grow to sufficient size to cause bulk damage.

Environmental effects are absent in a low-oxygen sodium environment and the fatigue data represent the true creep-fatigue behavior of Fe-2 1/4Cr-1Mo steel. Fatigue results obtained in an air environment should correctly be termed creep-fatigue-environment interaction. Depending on the time, temperature, and test conditions, oxidation effects may completely dominate fatigue life such that the creep-fatigue interaction is negligible.

Several analytical methods have been proposed for predicting the creep-fatigue or time-dependent fatigue behavior of materials. The Linear Damage Rule considers fatigue and creep damage to be independent of each other. Fatigue damage is expressed as a cycle fraction and is determined from the continuous-cycle fatigue data, whereas creep damage is expressed as a time fraction and is obtained from the stress rupture data. However, the Linear Damage Rule assumes equal damage for tensile and compressive stresses. Therefore, it predicts equal fatigue life for slow-fast and fast-slow tests at a given strain rate and strain range. The Modified Frequency Separation method expresses the tension-going and compression-going halves of the fatigue cycle by two average frequencies. This method predicts the reduction in life due to tensile-hold or slow-fast tests to be equal to the increase in life due to fast-slow tests compared to symmetric cycling fatigue.

In view of the limitations of the above-mentioned life prediction methods, the fatigue and creep-fatigue data in sodium were analyzed using the Damage Rate Approach.[15] The method considers an interaction between the fatigue crack and cavity growth. It assumes that either the cavities spontaneously anneal out under compressive stress or the crack does not interact with the cavities when they are below a critical size. For different waveshapes, the fatigue life, N_f, is related to the plastic strain range, $\Delta\varepsilon_p$, and plastic strain rate, $\dot{\varepsilon}_p$. Thus, for symmetric cycling,

$$N_f = \frac{m + 1}{2A} (\Delta\varepsilon_p)^{-(m+1)} \dot{\varepsilon}_p^{1-k} \qquad (1)$$

and

$$A = (T + C)/[2\ln(a_f/a_0)], \qquad (1a)$$

where m, k, T, and C are material parameters and a_f and a_0 are the final and initial crack size, respectively. For a fast-slow strain sequence, cavities are not initiated in the material and the fatigue life is given by

$$N_f = \frac{m + 1}{2A} (\Delta\varepsilon_p)^{-(m+1)} \left[\frac{\dot{\varepsilon}_f^{k-1}}{1 + C/T} + \frac{\dot{\varepsilon}_s^{k-1}}{1 + T/C}\right]^{-1}, \qquad (2)$$

where $\dot{\varepsilon}_f$ and $\dot{\varepsilon}_s$ are the fast tensile and slow compressive plastic strain rates, respectively. In the absence of strain rate effects, Eq. (2) reduces to Eq. (1), i.e., it predicts identical lives for fast-slow and constant strain rate tests. When strain rate effects are excluded, the fatigue life for slow-fast tests (i.e., slow tensile plastic rate, $\dot{\varepsilon}_s$, followed by fast compressive plastic strain rate, $\dot{\varepsilon}_f$) is given by

$$N_f = \left[-1 + \left\{1 + 2BA_g(m + 1)\Delta\varepsilon_p^{-(m+1)}L\right\}^{1/2}\right] \Big/ (BA_g), \qquad (3)$$

$$B = \frac{1}{m + 1} \Delta\varepsilon_p^{(m+1)} \left[\dot{\varepsilon}_s^{k_c-1} - \dot{\varepsilon}_f^{k_c-1}\right],$$

where A_g is the parameter that describes the interaction between the fatigue crack and cavities, $L = 1/2A$, and k_c is a material constant obtained from creep rupture data.

For continuous-cycle fatigue data in sodium, the strain rate exponent $k = 1$. The material parameters A and m were obtained from the continuous-cycle data and the parameter A_g from the slow-fast data. Since the environment has little or no effect on the bulk properties, the creep exponent k_c was determined from the creep rupture data in air. The various parameters of the Damage Rate equations for the creep-fatigue behavior of Fe-2 1/4Cr-1Mo steel in sodium are given in Table I.

TABLE I. Material Parameters for Evaluation of the Creep-Fatigue Behavior of Fe-2 1/4Cr-1Mo Steel in a Sodium Environment at 755, 811, and 866 K by the Damage Rate Approach

Parameter	Isothermally Annealed Material	Aged or Sodium-exposed Material
A	1.50	2.06
m	1.0	1.0
k	1.0	1.0
A_g, 755 K	0.11	0.11
811 K	0.72	0.72
866 K	5.88	5.88
k_c	0.7	0.7

The parameters obtained from the slow-fast and constant strain rate tests were used to predict the fatigue life for tensile-hold-time tests. The fatigue life for tests with a hold period is given by

$$N_f = [-1 + \{1 + (2D/D_T)\}^{1/2}]/D, \qquad (4a)$$

where

$$D_T = \frac{2A}{m+1} \Delta\varepsilon_p^{(m+1)} \qquad (4b)$$

and

$$D = \frac{A_g}{m+1} \Delta\varepsilon_{p_1}^{(m+1)} \dot{\varepsilon}_{p_1}^{k_c-1} - \frac{A_g}{m+1} \Delta\varepsilon_{p_2}^{(m+1)} \dot{\varepsilon}_{p_2}^{k_c-1} + A_g \int |\varepsilon_p|^m \dot{\varepsilon}_p^{k_c} \, dt; \qquad (4c)$$

$\Delta\varepsilon$ and $\dot{\varepsilon}$ are the plastic strain range and strain rate during the tension-going cycle (subscript p_1), compression-going cycle (subscript p_2), and hold period (subscript p). Figure 7 shows the predicted strain-life relationships for constant-hold periods up to 360 ks (100 h). The stress relaxation behavior for constant-strain hold-time tests in air was used in computing these strain-life curves. The results show that the creep-fatigue interaction is strongly dependent on temperature. Fatigue life is reduced by a factor of ~10 for a 360-ks tensile-hold time at 866 K, and only by a factor of ~2 for a similar tensile-hold period at 755 K. At all temperatures, the reduction in life for compressive-hold periods is minimal.

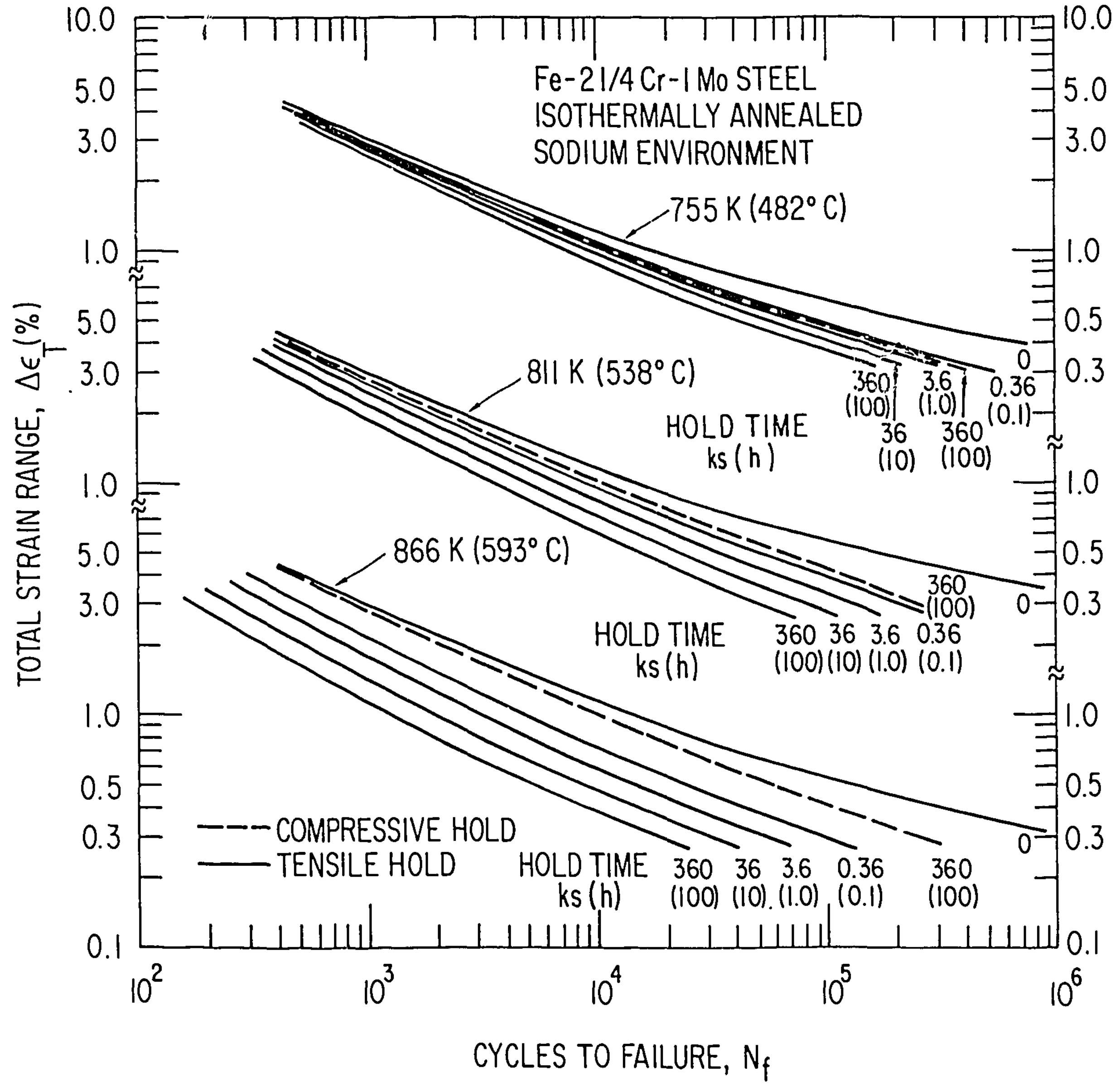

Fig. 7. Long-Term Creep-Fatigue Behavior of Isothermally Annealed Fe-2 1/4Cr-1Mo Steel in Sodium, as Predicted by Use of the Damage Rate Equations.

SUMMARY

Mechanical property data on isothermally annealed, thermally aged, and sodium-exposed Fe-2 1/4Cr-1Mo steel have been analyzed to predict the long-term effects of a high-temperature sodium environment. Both thermal aging and decarburization of the steel in sodium result in degradation of the mechanical properties relative to those of the isothermally annealed steel. At temperatures <823 K (550°C), degradation is essentially due to thermal aging. Loss of carbon from Fe-2 1/4Cr-1Mo steel reduces both the tensile and creep-rupture strength, but has little or no effect on the fatigue properties. Based on the kinetics of decarburization of isothermally annealed Fe-2 1/4Cr-1Mo steel in sodium at 783 K (510°C), the total carbon loss from superheater tubing during the service lifetime is expected to be ~0.04 wt %. A carbon loss of 0.04 wt % would result in an ~5% loss of tensile strength and an ~12% loss of creep strength.

Fatigue data on Fe-2 1/4Cr-1Mo steel in sodium indicate that the environment itself has no deleterious effects. In a sodium environment of controlled purity, the cyclic properties of Fe-2 1/4Cr-1Mo steel are superior to those in air. The plastic strain-life relationship in sodium is independent of temperature and strain rate. A compressive-hold period has no effect on fatigue life in sodium whereas a tensile-hold period reduces fatigue life. The reduction in fatigue life is greater at higher temperatures. Specimens tested with a slow-fast strain sequence or tensile-hold period show bulk cavitation. Metallographic observations indicate that cavity damage, which occurs during tensile straining, can anneal out during identical compressive straining. The creep-fatigue data were analyzed using interactive damage rate equations to predict the time-dependent fatigue behavior of isothermally annealed Fe-2 1/4Cr-1Mo steel in sodium.

Acknowledgments

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