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CREEP-FATIGUE EFFECTS IN STRUCTURAL MATERIALS USED IN ADVANCED NUCLEAR POWER GENERATING SYSTEMS

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ABSTRACT

We review various aspects of time-dependent fatigue behavior of a number of structural alloys in use or planned for use in advanced nuclear power generating systems. Materials included are types 304 and 316 stainless steel, Fe-2 1/4 Cr-1 Mo steel, and alloy 800H. Examples of environmental effects, including both chemical and physical interaction, are presented for a number of environments. The environments discussed are high-purity liquid sodium, high vacuum, air, impure helium, and irradiation damage, including internal helium bubble generation.

INTRODUCTION

Time-dependent fatigue behavior of structural steels proposed for use in advanced nuclear power generating systems has been under investigation for approximately 15 years in the United States. However, while a cursory understanding of the complex mechanisms involved has been achieved, the ability to extrapolate relatively short-term uniaxial laboratory-generated data with confidence to design times of 30 to 40 years is not yet possible. Therefore, our objective is to review state-of-the-art understanding of time-dependent fatigue behavior of several structural alloys by using recently generated data and published results. These alloys are being characterized for use in a number of nuclear fission and

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fusion devices. Ongoing efforts in data generation for model development purposes will also be briefly discussed.

The materials to be considered will be those associated with the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code, Case N-47 and are as follows: types 316 and 304 stainless steel, Fe-2 1/4 Cr-1 Mo steel, and alloy 800H.

Specific examples used here to show environmental interaction and the complexities of time-dependent fatigue involve liquid sodium, high vacuum, air, impure helium, and irradiation damage.

ENVIRONMENTAL INTERACTION AND TIME-DEPENDENT FATIGUE IN FAST BREEDER REACTOR SYSTEMS

High-purity liquid sodium is the heat transfer medium or core coolant for many planned as well as operating fast breeder reactor systems. In part this results from its excellent heat transfer characteristics and lack of deleterious effects on the mechanical properties of structural steels, provided that the oxygen[1] and carbon contents,[2] as well as other liquid-metal embrittling elements such as lead, tin, and antimony, are carefully controlled.[3] However, factors such as composition of the individual structural alloy, exposure temperature and time, etc. must also be taken into account.[4]

In addition to the chemical effects, the physical effects of sodium, such as good heat transfer properties, must be considered. The effects of reactor trips as well as sodium streams that are at different temperatures mix while impinging upon component surfaces and produce local differences in temperatures. These effects may produce time-dependent or independent fatigue damage depending upon their frequency. Reactor trips (power changes, startups, or shutdowns) are relatively infrequent, perhaps with up to 1000 occurring over the design lifetime of the plant. However, large changes in stress level can occur with resultant low-cycle creep-fatigue damage possible. Impingement of sodium at different temperatures or thermal striping on the surface of above-core structural components or at mixing tees produces a possible high-cycle fatigue (10^9 cycles) problem. In liquid-metal fast breeder reactor systems these combinations of high- or low-cycle time-dependent fatigue interactions are addressed by particular care in design, by proper selection of materials, and by extensive material characterization programs.

Austenitic Stainless Steels

Types 304 and 316 austenitic stainless steels are used extensively as vessel, piping, core support, and heat exchanger materials in fast breeder reactor systems.[5] These components can accrue creep-fatigue damage as a consequence of exposure to thermal transients, as discussed above. For these reasons a long-term creep-fatigue program has been and continues to be under way at Argonne National Laboratory. The objective of this program is to generate data on types 304 and 316 stainless steel from specimens with failure times ranging to three years. Figure 1 summarizes much of the data currently available from this program plotted in a "t-N_f" or log total test time-vs-log cycles to failure diagram for various strain ranges and tensile hold times.[6] All the data came from tests conducted in air and in strain control with the indicated hold periods at the peak tensile strain point on the hysteresis

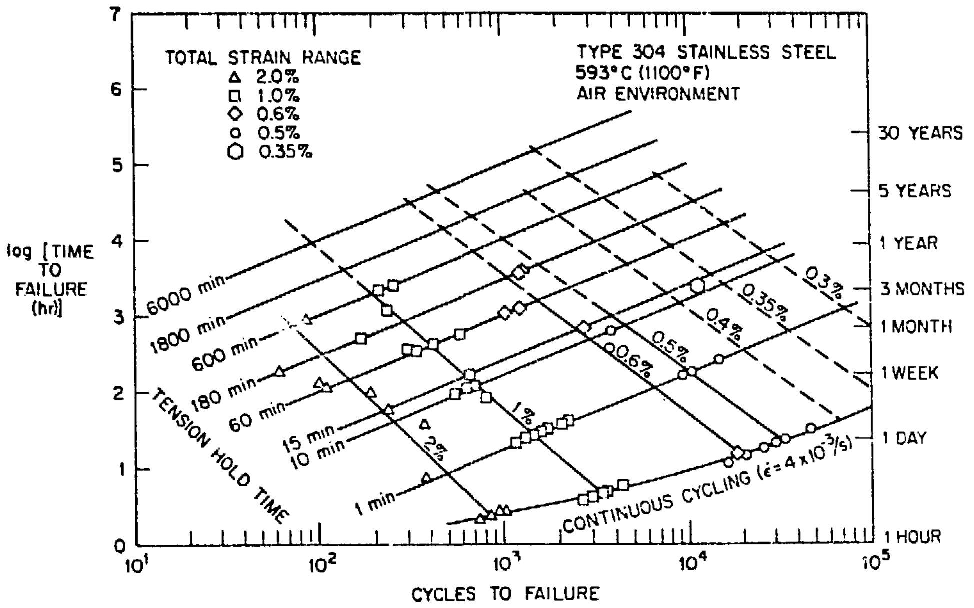


Fig. 1. Time to failure vs cycles to failure showing the influence of tensile hold times on the fatigue life of type 304 stainless steel. Source: C. R. Brinkman, V. K. Sikka, M. K. Booker, "An Overview of the U.S. Programs on Properties of Primary Circuit Materials," pp. 13–23 in Specialist Meeting on Primary Circuit Materials Including Environmental Effects, IWGFR/22, International Atomic Energy Agency/International Working Group on Fast Reactors, Bergisch Gladbach, Federal Republic of Germany, October 17–21, 1977.

loop. The data show a continued degradation in fatigue life with increasing duration of hold time with no indication of saturation of the hold-time effect.

Environments that limit or prevent surface oxidation at high temperatures typically result in marked improvements in the continuous cycle life of types 304 and 316 stainless steel. Comparison of data[7] generated from specimens tested in high vacuum with air data indicated an improvement in cycle life with factors ranging from 3 to 5 at strain ranges from 0.5 to 2.0%. In sodium with 1 to 2 ppm oxygen a similar beneficial effect is noted in comparison with data generated in air particularly at low strain ranges. This beneficial effect of sodium has tentatively been attributed to improved crack nucleation resistance, as fewer surface cracks are noted on post-test examination for specimens tested in sodium in comparison with specimens subjected to identical test parameters in air.[8] On the other hand, a decrease in crack growth rates is also observed in compact tension specimens tested in sodium in comparison with those similarly tested in air.[2]

Figure 2 compares strain-controlled low-cycle fatigue data for type 304 stainless steel generated both with and without tensile hold times at 593°C and at a single strain range. The data show

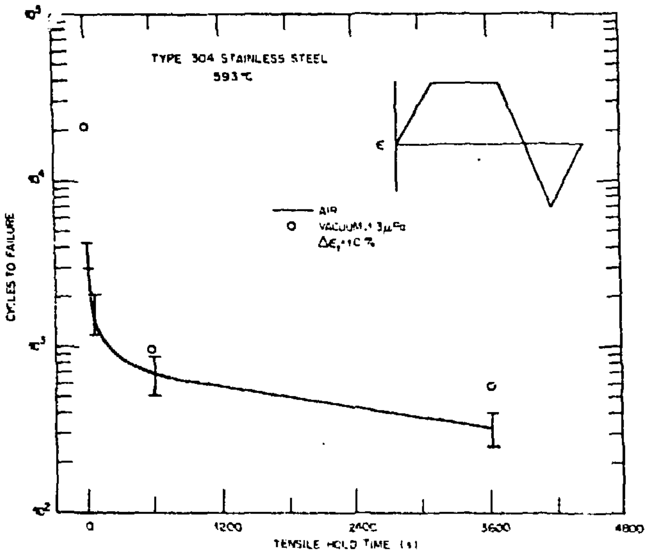


Fig. 2. Degradation of fatigue life resulting from tensile hold times becomes nearly the same as the length of the hold period increases for high vacuum and air environments. Source: P. S. Maiya, "Effects of Waveshape and Ultra-High Vacuum on Elevated Temperature Low-Cycle Fatigue in Type 304 Stainless Steel," submitted to <u>Materials Science and Engineering</u>.

that large differences exist for cycle life between continuous cycle data ($\dot{\varepsilon}$ = 4 × 10^{-3}/s) generated in air and under high vacuum [(1.3 × 10^{-6} Pa (10^{-8} torr)]. However, these differences tend to be minimal as the length of the tensile hold time increases. A similar conclusion has been reached in comparing limited results of strain-controlled tests conducted on type 316 stainless steel tested in high purity sodium.[8] The significance of waveform in producing creep damage that leads to intergranular fracture in type 304 stainless steel[7] is shown in Fig. 3. Here the ratio of cycle life in vacuum to cycle life in air is plotted against plastic strain range. Tensile strain-controlled hold times or triangular "slow-fast" ramp rates lead to intergranular fracture with the result that high vacuum tends to be less important than when the waveform imposed leads to transgranular fatigue crack propagation. These results tend to demonstrate a true creep-fatigue effect fot this material. That is, degradation in cycle life under conditions that produce considerable intergranular cavitation and crack propagation primarily results from creep damage rather than environmental interaction, as has been suggested by several investigators.[9,10] Sadananda et al.[11] similarly have concluded from crack growth studies conducted on several austenitic stainless steels tested in vacuum [1.3 × 10^{-4} Pa (10^{-6} torr)] and in air that enhanced crack growth under hold times primarily results from creep-fatigue interaction.

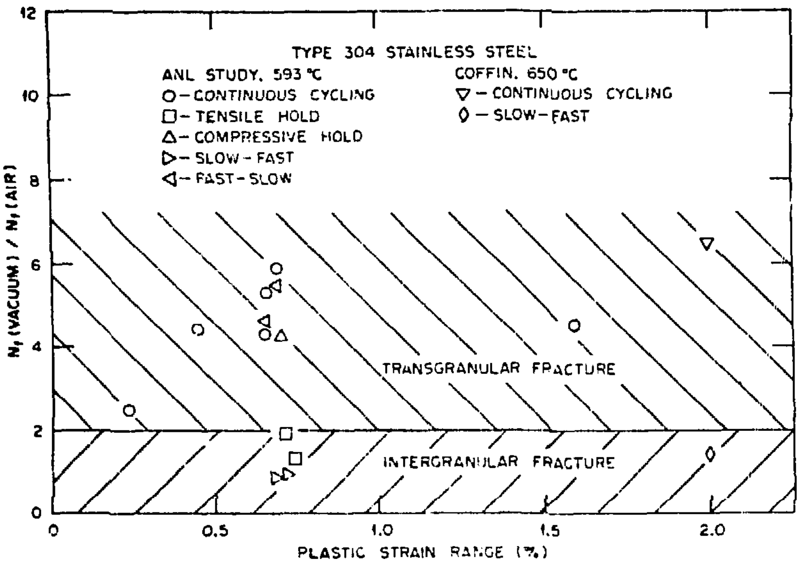


Fig. 3. Effect of waveshape and environment on fracture mode. Source: P. S. Maiya, "Effects of Waveshape and Ultra-High Vacuum on Elevated Temperature Low-Cycle Fatigue in Type 304 Stainless Steel," submitted to Materials Science and Engineering.

Recently investigators conducting strain-controlled exploratory fatigue tests on the austenitic stainless steels in both the United States and Japan[12] have been imposing hold periods on the hysteresis loop each cycle at locations other than peak tensile or compression values. An example of this effort is shown in Fig. 4 for type 304 stainless steel tested at 650°C in air[12] Here a strain hold period of 0.17 h (10 min) for the example shown is introduced at the same point on the hysteresis loop each cycle until failure. These tests are being conducted to generate a data base for model substantiation or development with hold periods imposed at locations such as zero stress, as shown, or at points on the hysteresis loop where little or no stress relaxation occurs. Data generated in air of the type shown in Fig. 4 tend to show the following:

1. Tensile hold times at peak strain values are more damaging than compression hold times of equal duration.

2. Hold periods imposed at other locations on the hysteresis loops, such as at zero stress or zero stress relaxation points, degrade fatigue life but not as much as hold periods imposed at peak tensile strain values.

3. Hold periods imposed on the tension-going side of the loop tend to be more deleterious than those imposed on the compression-going side.

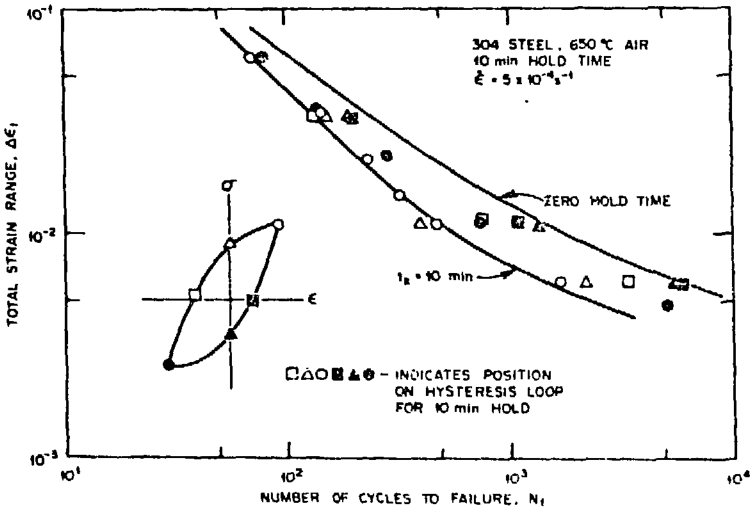


Fig. 4. Results of Japanese exploratory creep-fatigue tests. Source: Y. Asda and S. Mitsuhashi, "Creep-Fatigue Interaction of 304 and 316 Stainless Steels in Air and Vacuum," paper presented at 4th International Conference on Pressure Vessel Technology, London, England, May 19–23, 1980.

Another area of current interest for design of fast breeder reactor systems is fatigue crack propagation. Recent results have shown that a phenomena called "accelerated crack propagation" can occur for particular combinations of waveform, hold-time duration, and perhaps metallurgical state.[13] Figure 5 shows an example for type 316 stainless steel tested in the thermally aged condition before testing at 593°C. The data show that when intergranular precipitate particles are present, combined static and dynamic

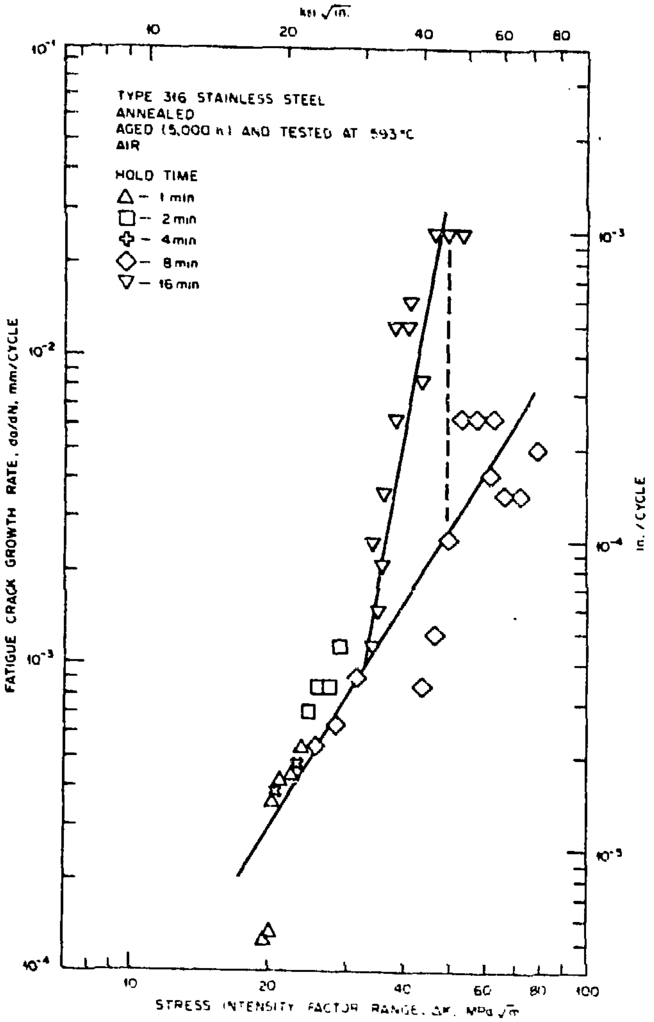


Fig. 5. Accelerated crack propagation in solution annealed, thermally aged 316 stainless steel tested at 593°C. Source: D. J. Michel and H. H. Smith, "Accelerated Creep-Fatigue Crack Propagation in Thermally Aged Type 316 Stainless Steel," to be published in Act. Metallurgica.

(zero to tension loading plus load-controlled) hold periods can lead to higher crack propagation rates. For the example shown, hold periods equal to or in excess of 0.27 h (16 min.) led to accelerated crack propagation rates associated with intergranular crack propagation. It is thought by some [13] that the increase in crack propagation rate is related to a critical cavity size and spacing associated with intergranular carbides. However, other investigators have not noted such a relationship.[14] Further, similar studies conducted on type 316 stainless steel in air at elevated temperatures have shown some evidence of environmental interaction.[14] Ongoing test efforts are expected to clarify the role of environment in producing accelerated crack growth behavior in this material.

Fe-2 1/4 Cr-1 Mo Steel

Fast breeder reactors presently in operation, as well as those planned for future operation, make extensive use of 2 1/4 Cr-1 Mo steel as a steam generator material.[15] This alloy, which will undergo prolonged exposure at temperatures within the creep range during a design lifetime of up to 30 years, will be subject to both time-dependent and time-independent fatigue damage. Accordingly, the material has been extensively characterized in the annealed condition for its fatigue properties.[16,17] Results from stain-controlled fatigue tests that were conducted in various environments over the temperature range of about 370 to 593°C on annealed material have shown that time-dependent fatigue lifetime depends upon the influence of the following:

1. environment or oxidation,
2. metallurgical state,
3. waveform and frequency,
4. classical creep damage.

At temperatures within the range of about 371 to 482°C, tensile and fatigue properties are dependent upon testing strain rate, primarily because of the effects of dynamic strain aging or interaction solid-solution hardening.[17,18] At temperatures in excess of approximately 450°C, time-dependent fatigue life in air is dependent upon the oxide scale (Fig. 6) that is formed and upon its behavior when the material is subjected to different waveforms.[18,19] Test data obtained in air and in strain control with either tensile or compressive hold times or with both tensile and compressive hold periods introduced each cycle have shown the following trends over the temperature range 427 to 593°C:

1. Compressive hold times are more damaging than tensile holds, particularly at low strain ranges where resistance to crack nucleation governs lifetime (Fig. 7).

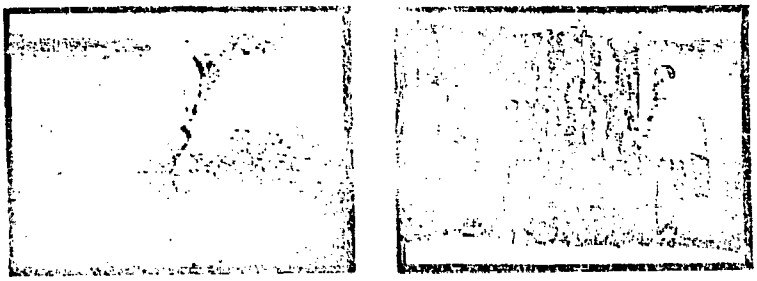


Fig. 6. A low-oxygen environment is a significant factor affecting elevated-temperature fatigue resistance. Surfaces of specimens tested in air show extensive oxidation compared with specimens tested in high-temperature gas-cooled reactor (HTGR) helium.

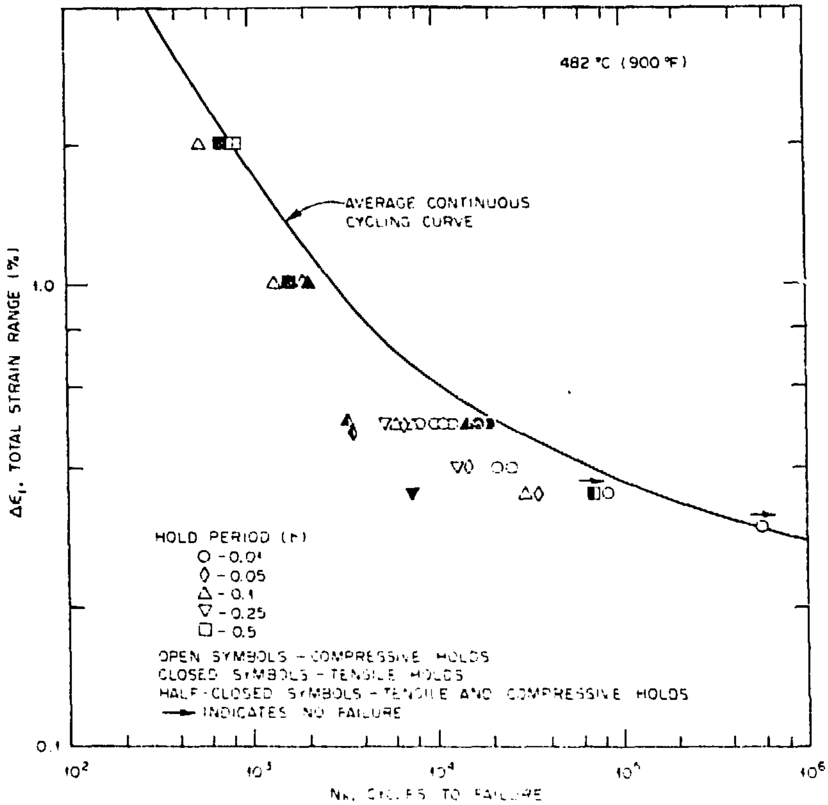


Fig. 7. Results of strain-controlled fatigue tests conducted on annealed 2 1/4 Cr-1 Mo steel with various hold periods.

2. A cycle with both a tensile and a compressive hold period at low strain ranges may be more damaging than the cycle with only a tensile or compressive hold with all hold periods of the same duration (Fig. 7).

Not all low-alloy steels that have been tested to date demonstrate this type behavior under cyclic and time-dependent loading conditions. For example, a rotor steel (1 Cr-Mo-V) that was extensively tested[20] indicated that tensile hold times were most damaging. Furthermore, compression holds when introduced into cycles that already contained tension holds were beneficial in that cycle life was improved (Fig. 8).

When tests are conducted at 538°C or higher in environments that limit or prevent oxidation [e.g., impure or high-temperature gas-cooled reactor (HTGR) helium (Fig. 9) or sodium[21] (Fig. 10)] tensile hold periods become more damaging for cycle life for annealed 2 1/4 Cr-1 Mo steel. Further, when a slow-fast waveform (i.e., 4×10^{-5}/s tension going and 4×10^{-3}/s compression going) was employed in low-oxygen sodium environment tests, grain

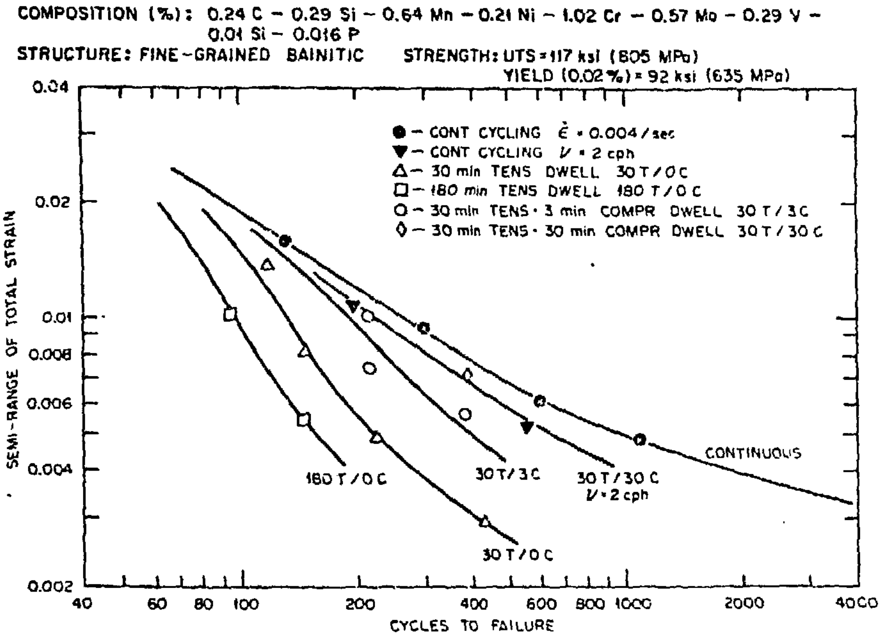


Fig. 8. Compression hold periods in conjunction with tensile hold periods improved the time-dependent fatigue behavior of a 1 Cr-Mo-V steel at 565°C. Source: E. G. Ellison and A.F.J. Patterson, "Behavior of a 1 Cr-Mo-V Steel Subject to Combinations of Fatigue and Creep Under Stain Control," Proc. Inst. Mech. Eng. London 190: 333–40 (1976)

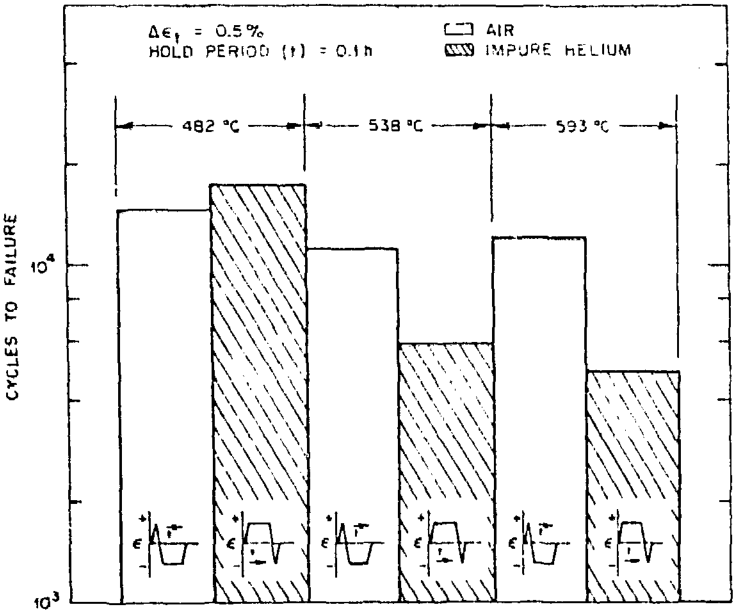


Fig. 9. Tensile hold times appear to be more damaging than compressive hold times in impure helium at temperatures equal to or in excess of 538°C.

boundary cavitation was seen on both the circumferential surfaces (at 482 and 538°C) (Fig. 11) and within the bulk (at 538°C) (Fig. 12) of the tested specimens, demonstrating classical creep damage.

Exploratory time-dependent and strain-controlled tests similar to those previously discussed for type 304 stainless steel have also been conducted on annealed 2 1/4 Cr-1 Mo steel. Figure 13 summarizes some of the results from these exploratory tests. All the tests were run in strain control at a single strain range and temperature with a hold period introduced each cycle at a single point on the hysteresis loop, as shown. The duration of the hold period was either 0 or 0.1 h, as indicated. Results of these tests conducted in air demonstrate the following for the particular strain range and temperature shown:

1. Compression holds are more damaging than tensile holds (6,111 vs 20,147 cycles to failure).

2. In comparison with zero hold-time or continuous cycle tests, tests conducted with a hold period introduced at zero stress points show decreased fatigue life: the average cycle life for

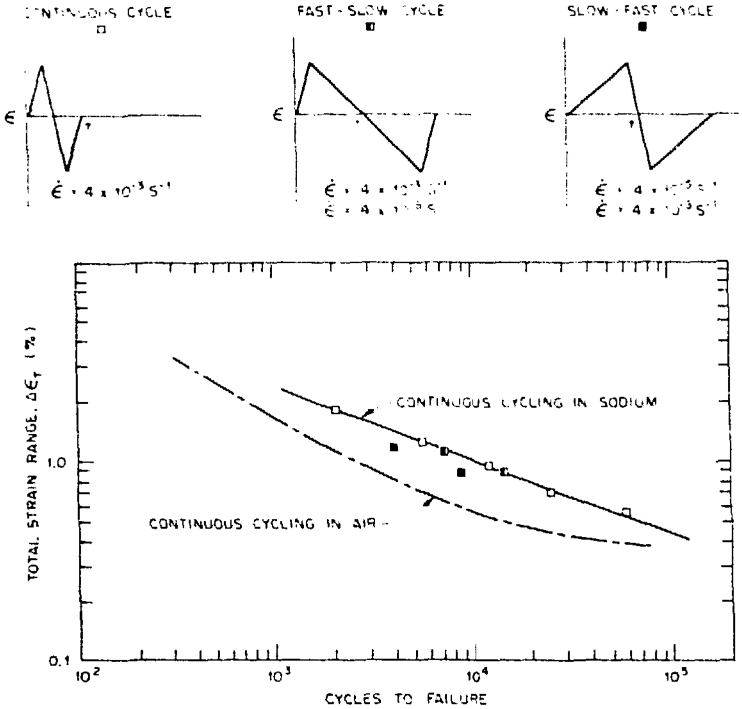
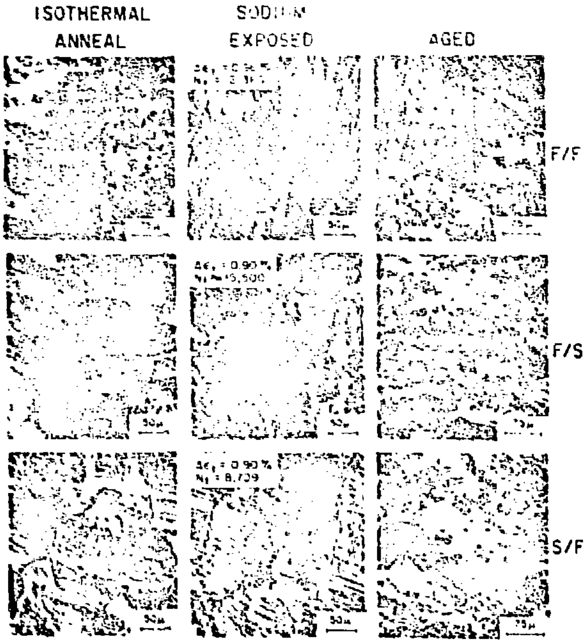


Fig. 10. Waveform is an important variable only in the slow-fast cycle for 2 1/4 Cr-1 Mo steel tested at 538°C in sodium. Source: O. K. Chopra, K. Natesan, and T. F. Kassner, "Influence of Sodium Environment on the Low Cycle Fatigue and Creep-Fatigue Behavior of Fe-2 1/4 Cr-1 Mo Steel," paper presented at Second International Conference on Liquid Metal Technology in Energy Production, Richland, Washington, April 10–24, 1980.

three specimens subjected to continuous cycling at a strain rate of 4×10^{-3}/s was 37,329 vs cycle lives of 6,317 and 15,557 for the zero stress points shown.

3. After continuous cycling at the indicated strain range, it was possible to locate points on the hysteresis loop in both tension and compression where little or no stress relaxation occurred (Fig. 14). A point in compression was at approximately −190 Mpa for the conditions indicated in Fig. 13, and the resultant fatigue life was 11,667 cycles to failure. This test again shows degradation in lifetime in comparison with the continuous cycle life at these conditions (i.e., 11,667 vs 37,329 cycles to failure).



TESTED AT:
538 °C 538 °C 482 °C

WAVEFORM:
F/F: $\dot{\epsilon} = 4 \times 10^{-3} s^{-1}$
F/S: $\dot{\epsilon} = 4 \times 10^{-3} s^{-1}$ AND $4 \times 10^{-5} s^{-1}$
S/F: $\dot{\epsilon} = 4 \times 10^{-5} s^{-1}$ AND $4 \times 10^{-3} s^{-1}$

SODIUM EXPOSED: PRE-AGED 3,000 h AT 538 °C IN SODIUM

AGED: PRE-AGED 5,000 h IN VACUUM AT 482 °C

Fig. 11. Results of scanning electron microscope examination of the circumferential surfaces of specimens of Fe-2 1/4 Cr-1 Mo steel fatigue tested in sodium. Note grain boundary cracks at boundaries perpendicular to direction of applied stress for slow-fast (S/F) waveform. Source: O. K. Chopra, K. Natesan, and T. F. Kassner, "Influence of Sodium Environment on the Low Cycle Fatigue and Creep-Fatigue Behavior of Fe-2 1/4 Cr-1 Mo Steel," paper presented at Second International Conference on Liquid Metal Technology in Energy Production, Richland, Washington, April 10–24, 1980.

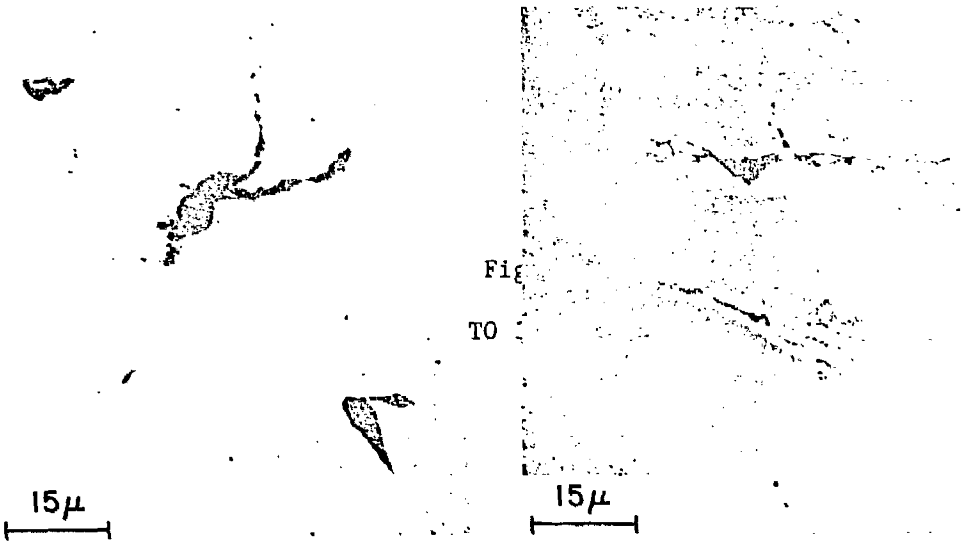


Fig. 12. Intergranular cavities were found in specimens of Fe-2 1/4 Cr-1 Mo steel subjected to slow-fast waveform at 538°C in sodium. Cavities of this type were not found in specimens similarly tested at 482°C. Source: O. K. Chopra, K. Natesan, and T. F. Kassner, "Influence of Sodium Environment on the Low Cycle Fatigue and Creep-Fatigue Behavior of Fe-2 1/4 Cr-1 Mo Steel," paper presented at Second International Conference on Liquid Metal Technology in Energy Production, Richland, Washington, April 10–24, 1980.

Examination of the surfaces of these specimens has shown that oxide interaction with the surface produces characteristic circumferential markings (Figs. 6 and 15), which are thought to decrease the number of cycles required for crack initiation with resultant reduction in cyclic life.[17-19] These markings are absent on the surface of specimens tested in nonoxidizing environments (Figs. 11 and 16).

It should also be noted that a protective environment that limits or prevents oxidation also markedly decreases high temperature crack propagation rates in comparison with data obtained in an air environment for this material.[22]

Linear damage summation of time and cycle fractions has been performed on the various tests shown in Fig. 13. The resultant D_t or total damage summation values are all less than 1.00 and tend not to sum to a unique value under strain or load-controlled conditions, making linear damage summation a questionable method for extrapolation, at least for air environments.

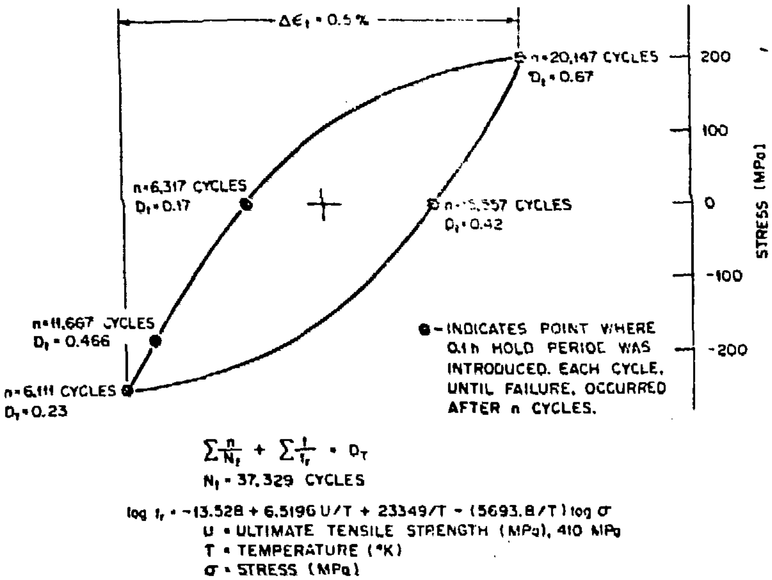


Fig. 13. Time and cycle fraction damage analysis for annealed 2 1/4 Cr-1 Mo steel heat 3P5601 tested at 482°C in air.

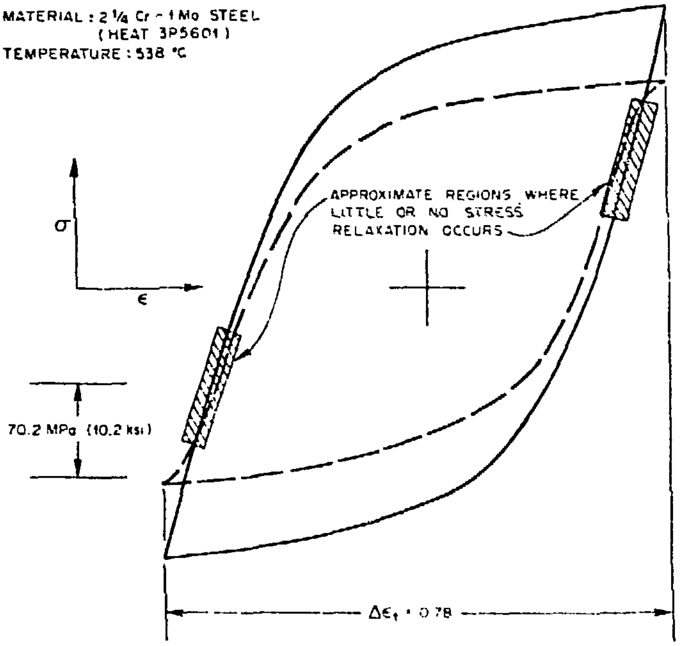


Fig. 14. Dashed lines represent locus of stress relaxation points following 0.1-h strain hold periods from various positions on the solid curve. Intersecting points represent positions of zero stress relaxation.

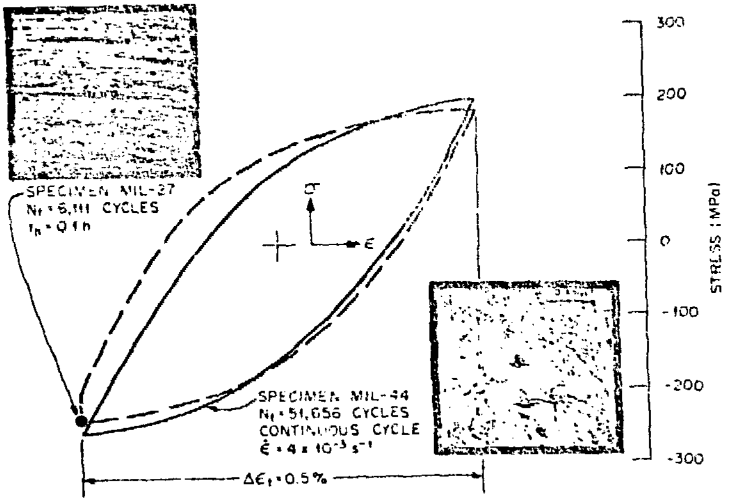


Fig. 15. Comparison of hysteresis loops, surfaces, and fatigue lives of two specimens subjected to strain control cycling at 482°C. Note that specimen MIL-36 had a 0.1-h hold period introduced each cycle at peak compressive strain.

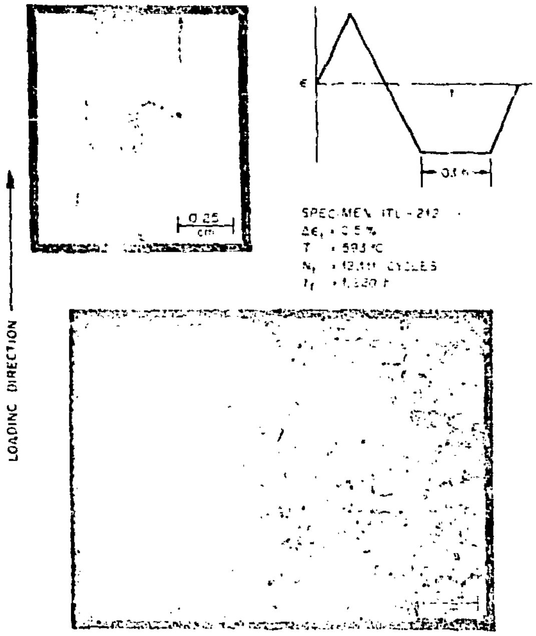


Fig. 16. The surface of a specimen of 2 1/4 Cr-1 Mo steel tested in impure helium in strain control with a compression dwell period each cycle.

Alloy 800H

Gas-cooled nuclear reactors presently under consideration, in which the coolant or heat transfer medium is helium with low levels of impurities, also require design for the prevention of time-dependent fatigue. The helium environment may be oxidizing, reducing, carburizing, decarburizing, depending on the alloy involved, the temperature, the moisture content, and the carbon potential of the gas relative to the carbon activity of the metal.[23] An example[24] of the effects of impure helium and air on the strain-controlled fatigue properties of alloy 800H tested at 650 and 760°C is given in Table 1. A comparison of the data shown follows.

Table 1. Impure Helium Environments that Can Produce Carburization Appear to Degrade Time-Dependent Fatigue Life of Alloy 800H Subjected to Tensile Hold Times[a]

Temperature (°C)	Strain Range (%)	Hold		Cycles to Failure	
		Mode	Time (min)	Impure Helium[b]	Air
650	0.4	0	0		>10^6
650	0.4	Tension	1	5,465	26,767
650	0.4	Tension	2.5	3,629	14,790
760	0.4	Tension	2.5	2,790	1,053
650	0.4	Compression	1	10,672	13,000
650	0.4	Compression	2.5	10,308	8,836
760	0.4	Compression	2.5	4,785	1,628

[a] Source: D. I. Roberts, S. N. Rosenwasser, and J. F. Watson, "Materials Selection for Gas-Cooled and Fusion Reactor Applications," paper 9 presented at Conference on Alloys for the 80's, Ann Arbor, Michigan, June 17–18, 1980.

[b] Helium composition, ppm: CH_4 = 50; CO = 50; H_2 = 500; H_2O = 1.

1. At low strain ranges compression hold periods are more damaging than tensile holds at 650°C in air, but the reverse appears to be true at 760°C.

2. Impure helium appears to cause a marked decrease in the fatigue life of specimens subjected to tensile hold times in comparison with similar tests conducted in air at 650°C. This is attributed to carburization.

There are indications that the magnitude of the hold-time effect in strain-controlled tests is dependent upon temperature and strain range as well as upon the magnitude and direction of any mean stress that is developed during a given test.

ENVIRONMENTAL INTERACTION AND TIME-DEPENDENT FATIGUE IN FUSION REACTOR FIRST-WALL SYSTEMS

Cyclic thermal stresses will occur in first-wall and blanket materials of pulsed fusion power generating devices. Because of this, fatigue data are currently being generated on candidate materials, including cold-worked type 316 stainless steel, refractory alloys, and a number of martensitic low-alloy steels with chromium contents in the range 9 to 13%. Environments or possible coolants associated with the first-wall and blanket structure may be liquid metals, gas, molten salts, or water. In addition, the first wall of a fusion reactor will also be subjected to intense high-energy neutron irradiation damage, causing atom displacement damage as well as helium and hydrogen generation.

The influence of high irradiation-induced helium contents and displacement damage on resultant tensile and fatigue properties of 20% cold-worked (20% reduction in area by swaging) type 316 stainless steel is currently being investigated.[25] A plot showing the effects of high helium content, etc. on the resultant strain-controlled fatigue properties of type 316 stainless steel is given in Fig. 17. Note the high scatter in the irradiated data and the resultant overall degradation in fatigue life, particularly at the low cycle end of the curve. Tensile ultimate strengths and reduction of area values were approximately 614 MPa and 36%, respectively, in comparison with unirradiated values of 650 MPa and 60%, near the indicated temperature and irradiation conditions. Figure 18 is a transmission electron micrograph showing extensive helium bubbles within the microstructure. At higher temperature helium bubbles at grain boundaries are thought to be particularly deleterious because of the probability of increased intergranular crack propagation rates under cyclic loading conditions.[26] Work dealing with the influence of irradiation on time-dependent fatigue properties, data analysis, and extrapolations has been published elsewhere.[27]

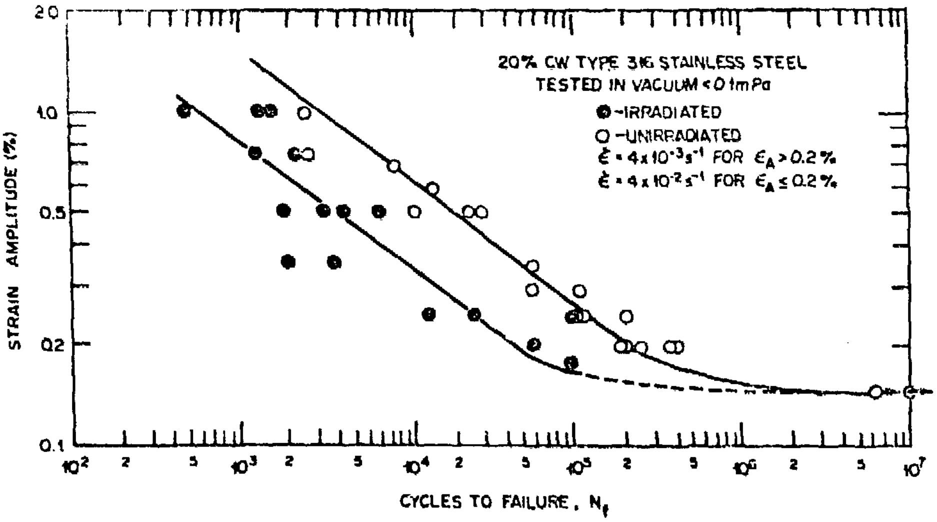


Fig. 17. Low cycle fatigue life is reduced by factors of 3 to 10 for 200 to 1000 ppm He and 5 to 15 dpa at 430°C, indicated endurance limit is at a strain amplitude of 0.15%. Source: M. L. Grossbeck and K. C. Liu, "Fatigue Behavior of Type 316 Stainless Steel Following Neutron Irradiation Inducing Helium," paper presented at American Nuclear Society meeting, La Vegas, Nevada, June 8–13, 1980.

Fig. 18. Microstructure of 20%-cold-worked type 316 stainless steel irradiated in the High Flux Isotope Reactor (HFIR) for 2,770 h at 470°C (12 dpa, 540 at. ppm He. Note the presence of helium bubbles randomly distributed throughout the matrix. Transmission electron micrograph courtesy of P. J. Maziasz, Oak Ridge National Laboratory.

SUMMARY AND CONCLUSIONS

Recently reported results from a number of ongoing materials data generating programs were reviewed. These programs are aimed at determining the influence of temperature, time, waveform, and environment on the elevated-temperature fatigue properties of several [illegible] alloys presently in use or planned for use in a number [illegible] nuclear power generating systems. Specific major [illegible] follows:

1. [illegible] such as high vacuum or high purity sodium that limit [illegible] oxidation result in a marked improvement in the continuous cycle fatigue life of types 304 and 316 stainless steel at temperatures within the creep range. However, when loading waveforms are employed such that intergranular crack propagation occurs, the differences in fatigue life tend to be minimal. This finding, particularly for long-term test results, supports the concept of a true creep-fatigue effect as a major contribution to the observed decrease in cycle life.

2. Exploratory strain-controlled fatigue tests conducted on type 304 stainless steel in air have shown that some degradation in fatigue life in comparison with continuous cycle tests can occur when hold periods are introduced at zero stress or zero relaxation points on the hysteresis loops. Similar tests conducted on annealed 2 1/4 Cr-1 Mo steel in air and at low strain ranges tend to show significant degradation in cycle life. This has been attributed to wave-form-oxide interaction that facilitates crack nucleation and accelerates crack propagation.

3. Cycle lives of specimens of 2 1/4 Cr-1 Mo tested in nonoxidizing environments, such as sodium, do not show the significant waveform dependency effects that are found for similar tests in air. However, slow-fast triangular waveforms at high temperature reduce cycle lives in sodium probably from the generation of grain boundary voidage.

4. Limited results of strain-controlled time-dependent fatigue tests conducted on alloy 800H in air have shown that the fatigue life is dependent upon cyclic waveform and strain range interaction and that a carburizing environment can be detrimental, depending again upon the cyclic waveform imposed.

5. Classical methods such as time and cycle fraction summation for predicting or extrapolating data appear questionable, particularly at temperatures where there is strong environmental interaction.

6. An example was selected for 20% cold-worked type 316 stainless steel to show that environments generated within a

structural material, such as the displacement damage and helium bubbles obtained by irradiation, must also be considered in design against fatigue damage when appropriate.

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