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A Status Report on Exploratory Time-Dependent Fatigue Behavior of 2 1/4 Cr-1 Mo and Modified 9 Cr-1 Mo Steel

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[redacted]

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David Hamrin
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A STATUS REPORT ON EXPLORATORY TIME-DEPENDENT FATIGUE BEHAVIOR OF 2 1/4 Cr-1 Mo AND MODIFIED 9 Cr-1 Mo STEEL*

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ABSTRACT

We review various aspects of time-dependent fatigue behavior of 2 1/4 Cr-1 Mo steel. Specifically, the roles of dynamic strain aging, environmental interaction, and classical creep damage (voidage) are discussed. Examples of results from exploratory test efforts show the strong waveform-environment synergism that occurs in this material. Plans are presented for future exploratory time-dependent fatigue testing of 2 1/4 Cr-1 Mo steel. Results indicate that the continuous-cycle fatigue resistance of modified 9 Cr-1 Mo is superior to that of standard 9 Cr-1 Mo steel and annealed 2 1/4 Cr-1 Mo steel in the high-cycle region. Limited results from time-dependent fatigue tests on modified 9 Cr-1 Mo steel have indicated that compressive hold periods are more damaging than tensile holds and that cyclic waveform effects similar to those seen in 2 1/4 Cr-1 Mo steel also occur in modified 9 Cr-1 Mo steel.

INTRODUCTION

Fast breeder reactors currently 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.[1] This alloy, which will undergo prolonged exposure at temperatures in 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.[2,3] Results from strain-controlled fatigue tests that were conducted in various

*Work performed under DOE/RRT AF 15 40 10.3, Task OR-1.3, Mechanical Properties Design Data.

environments from about 370 to 593°C on annealed material have shown that time-dependent fatigue lifetime depends on the influence of (1) metallurgical state, (2) waveform and frequency, (3) environment or oxidation, and (4) classical creep damage.

The objective of this report is to review briefly the effects of the above factors on the time-dependent fatigue behavior of 2 1/4 Cr-1 Mo steel (annealed condition) and to detail results of ongoing exploratory tests that have been aimed at further elucidating the operating mechanisms of creep-fatigue interaction in this material. Tentative plans for additional exploratory tests are also given. Finally, limited comparisons of the fatigue behavior of modified 9 Cr-1 Mo steel, including limited results from exploratory tests, are presented.

BACKGROUND

Low-Temperature Effects — 2 1/4 Cr-1 Mo Steel

At temperatures ranging from about 371 to 482°C, tensile and fatigue properties depend on testing strain rate or frequency, primarily because of the effects of dynamic strain aging or of interaction solid-solution hardening.[3,4] These effects can be seen in Fig. 1, in which the fatigue lives of several heats of annealed material are plotted as a function of temperature, carbon content, and strain rate. The effect on fatigue life is related to the amount of carbon in solution. All the heats shown had carbon contents in the range of 0.11 to 0.14 wt % except the low-carbon heat (50557), which had a carbon content of 0.02 wt %.

The effects of dynamic strain aging are particularly pronounced at low strain ranges. In fact, the high-cycle fatigue curve ($\dot{\varepsilon} = 4 \times 10^{-3}$/s) at room temperature has been demonstrated[5] to lie below the curve at 316°C.

High-Temperature Effects — 2 1/4 Cr-1 Mo Steel

At temperatures above 450°C, time-dependent fatigue life in air may depend on the oxide scale (Fig. 2) that is formed and its behavior when the material is subjected to different waveforms.[4,6] Test data obtained

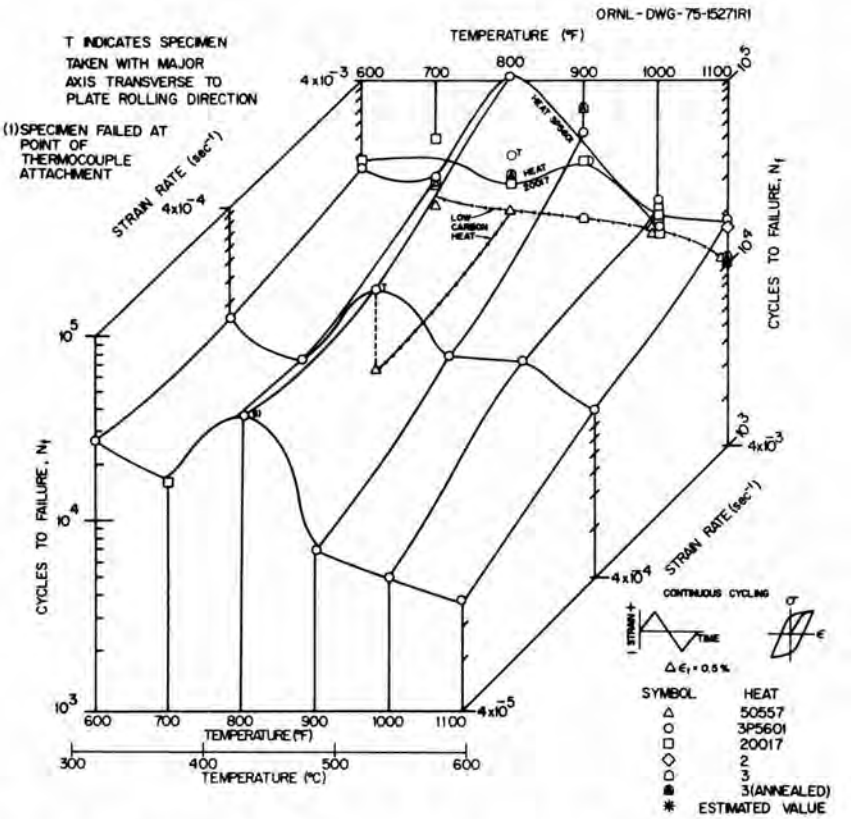

Fig. 1. Cycles to failure as a function of temperature and strain rate for 2 1/4 Cr-1 Mo steel in the annealed or isothermally annealed condition. Note the dynamic strain aging peak in cycle life that occurs over the temperature range of 375 to 482°C.

Fig. 2. 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.

in air and in strain control either with tensile or compressive hold times or with both tensile and compressive hold times introduced in each cycle have shown the following trends at temperatures ranging from 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. 3).

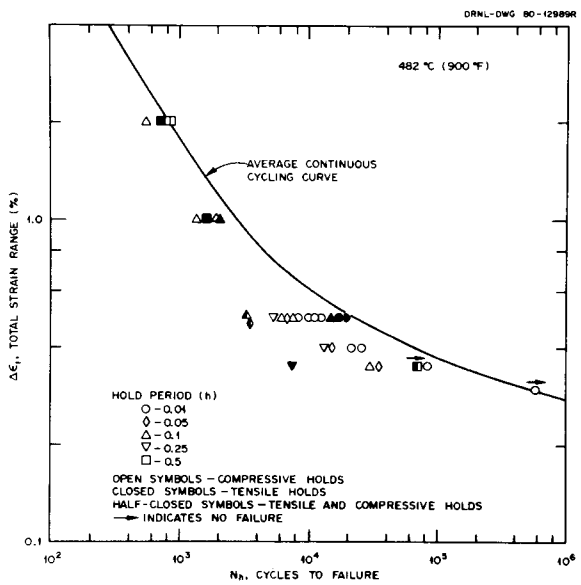

Fig. 3. Results of strain-controlled fatigue tests conducted on annealed 2 1/4 Cr-1 Mo steel with various hold periods.

2. A cycle with both a tensile and a compressive hold period at low strain ranges may be more damaging than the cycle having only one tensile or compressive hold and with all hold periods of the same duration (Fig. 3).

Not all low-alloy steels tested to date demonstrate this type of behavior under cyclic and time-dependent loading conditions. For example, an extensively tested rotor steel (1 Cr-Mo-V)[7] indicated that tensile hold times were most damaging. Furthermore, when introduced into cycles that already contained tension holds, compression holds improved the cycle life (Fig. 4).

When tests are conducted at 538°C or higher in environments that limit or prevent oxidation [impure or high-temperature gas-cooled reactor helium (Fig. 5) or sodium (Fig. 6)], tensile hold periods become more

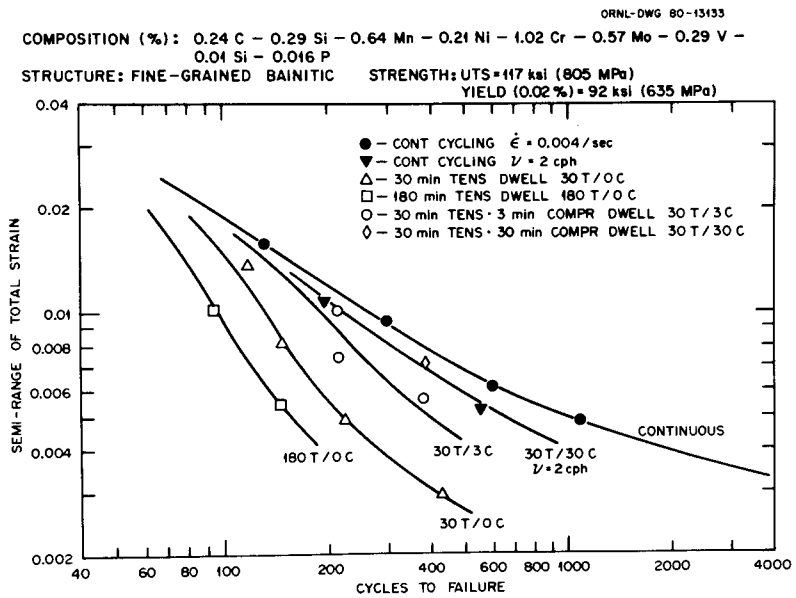

Fig. 4. Compression hold periods in conjunction with tension hold periods improved the time-dependent fatigue behavior of a 1 Cr-Mo-V steel at 565°C. Source: Based on data from E. G. Ellison and A.F.J. Patterson, "Behavior of a 1 Cr-Mo-V Steel Subject to Combinations of Fatigue and Creep Under Strain Control," *Proc. Inst. Mech. Eng. London* 190: 333–40 (1976).

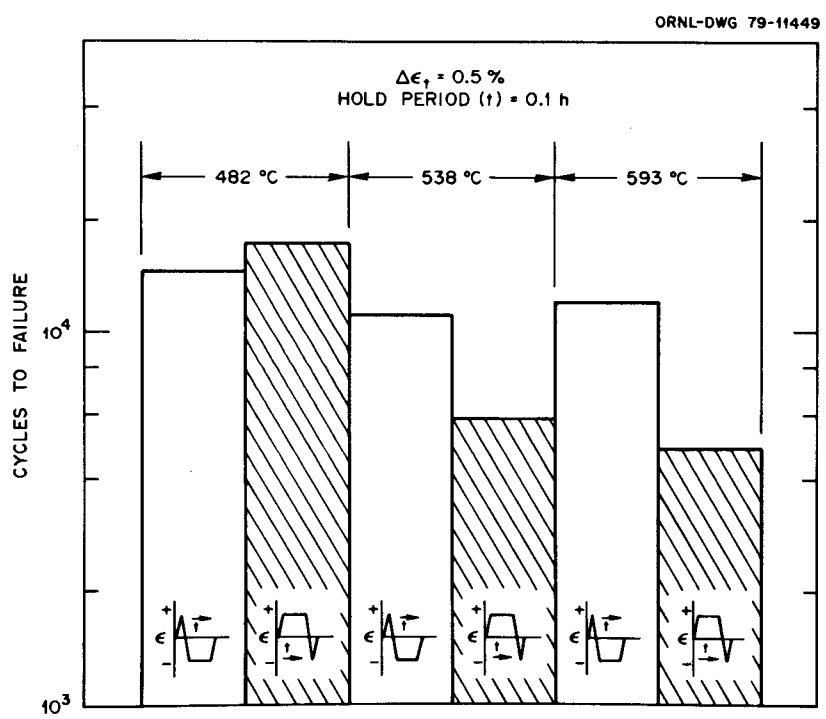

Fig. 5. Tensile hold times appear to be more damaging than are compressive hold times in impure helium at 538°C or above. Shaded regions represent cycle lives of tests conducted in impure helium compared to cycle lives of identical tests conducted in air (unshaded regions).

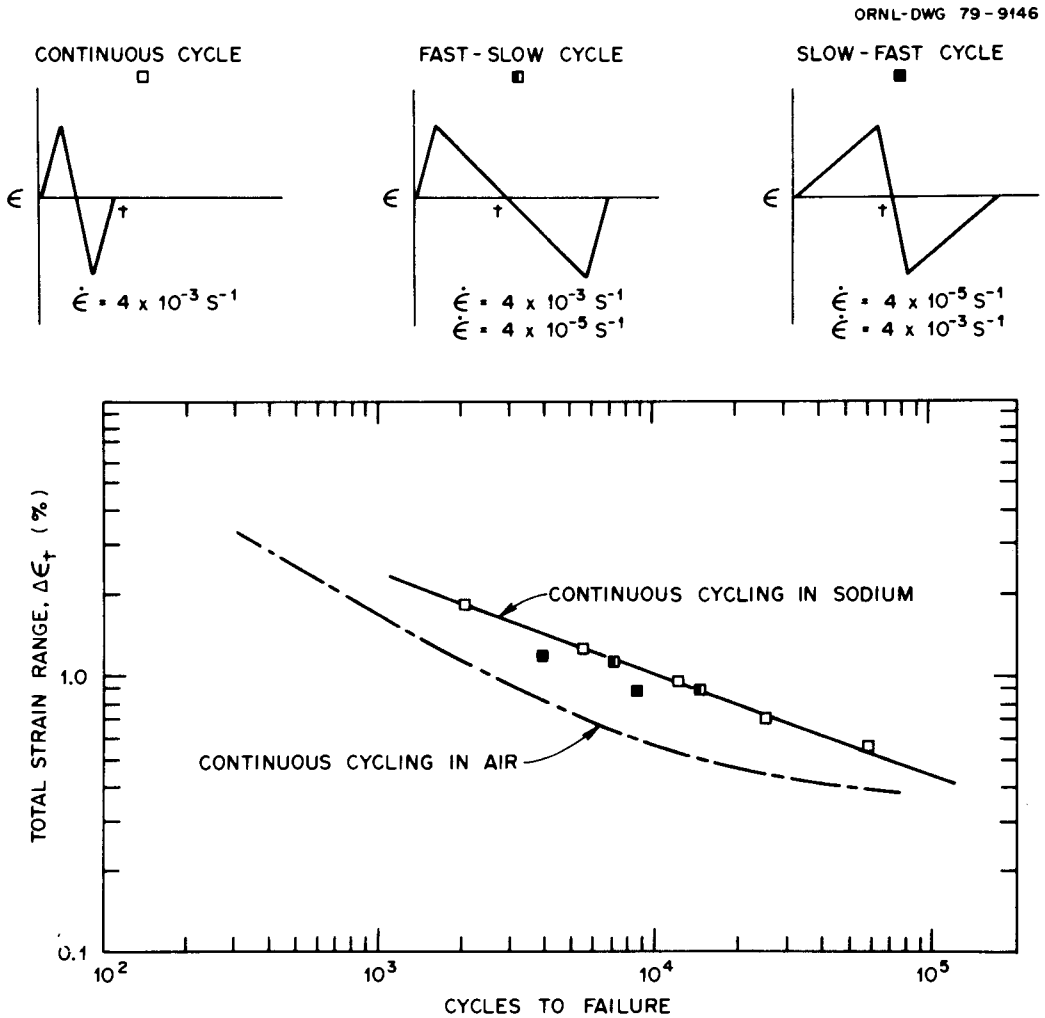

Fig. 6. Waveform is an important variable only in the slow-fast cycle for 2 1/4 Cr-1 Mo steel tested at 538°C in sodium. Source: From O. K. Chopra, K. Natesan, and T. F. Kassner, "Influence of Sodium Environment on the Low Cycle Fatigue and Creep-Fatigue Behavior of Fe-2 1/4 Cr-1 Mo Steel," paper presented at Second International Conference on Liquid Metal Technology in Energy Production, Richland, Washington, April 10–24, 1980.

damaging to cycle life for annealed 2 1/4 Cr-1 Mo steel.[8] Further, when a slow-fast waveform (4×10^{-5}/s tension-going and 4×10^{-3}/s compression-going) was employed in low-oxygen sodium environment tests, grain boundary cavitation was seen on both the circumferential surfaces (at 482 and 538°C) (Fig. 7) and within the bulk (at 538°C) (Fig. 8) of the tested specimens, demonstrating classical creep damage.[9]

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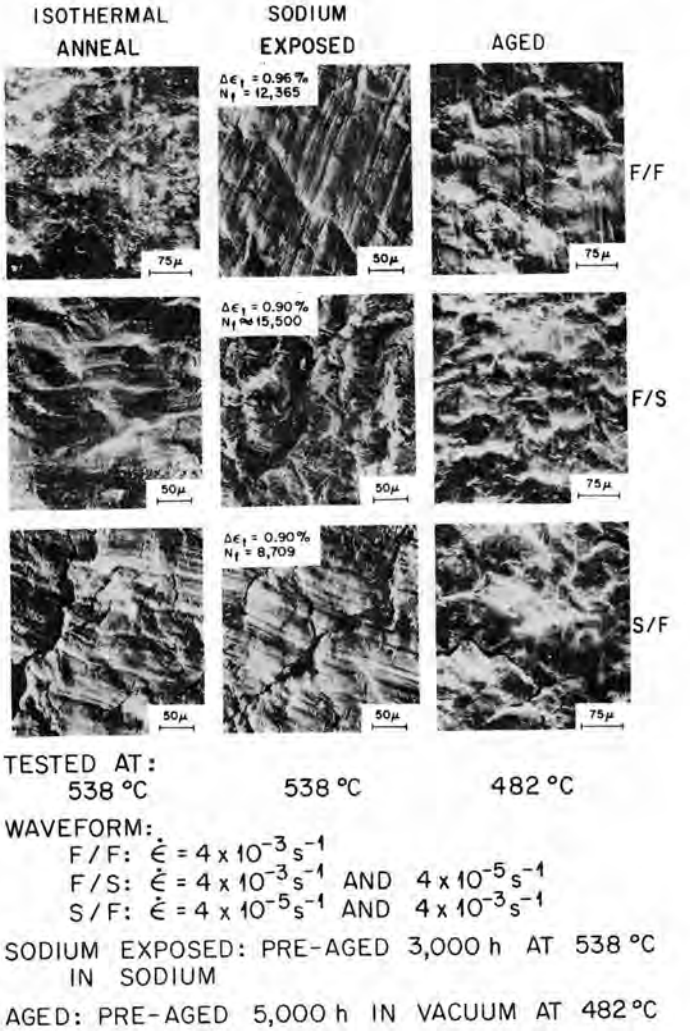

Fig. 7. Results of scanning electron microscope examination of the circumferential surfaces of specimens of 2 1/4 Cr-1 Mo steel fatigue-tested in sodium. Note grain boundary cracks at boundaries perpendicular to direction of applied stress for slow-fast (S/F) waveform. Source: From O. K. Chopra, K. Natesan, 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.

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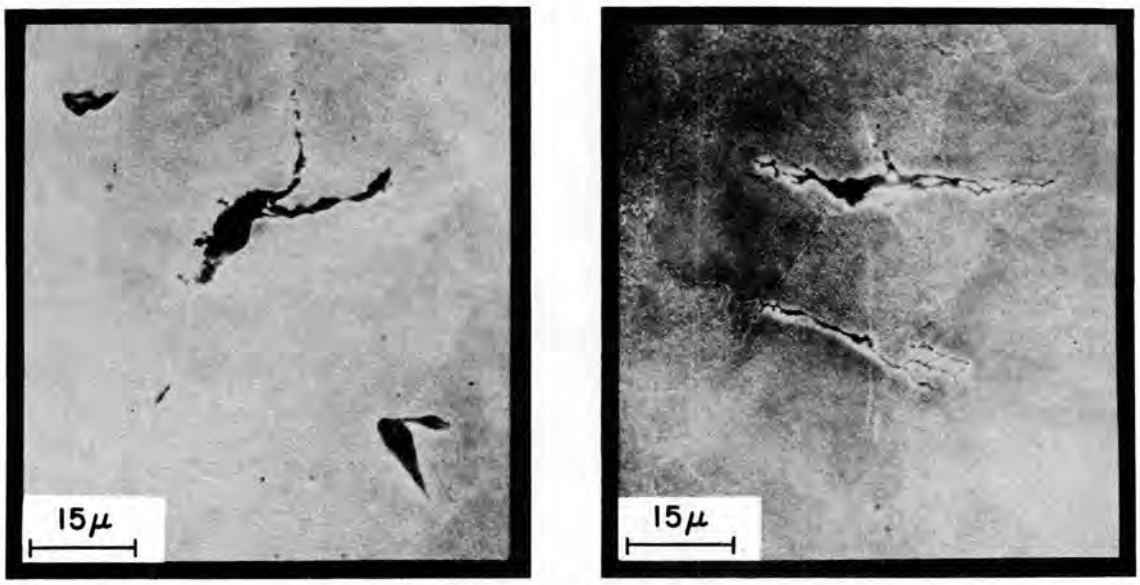


Fig. 8. Intergranular cavities found in specimens of 2 1/4 Cr-1 Mo steel subjected to slow-fast waveform at 538°C in sodium. Cavities of this type were not found in specimens similarly tested at 482°C. Source: From O. K. Chopra, K. Natesan, and T. F. Kassner, "Influence of Sodium Environment on the Low 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.

EXPLORATORY TESTS

Annealed 2 1/4 Cr-1 Mo Steel

Exploratory time-dependent uniaxial fatigue tests are in progress on annealed 2 1/4 Cr-1 Mo steel at temperatures ranging from 482 to 538°C. The objectives of this effort are

1. To conduct fully reversed strain-controlled isothermal and non-isothermal tests with complex strain or load waveforms. The data derived from such studies will be used to test various proposed models and models that are evolving for correlating and extrapolating time-dependent fatigue data.

2. To conduct tests in both air and inert environments to determine the role that environment plays in time-dependent fatigue behavior.

Results of tests conducted to date in this series are given in Table 1, and Fig. 9 summarizes some of the results from tests at 482°C.

Table 1. Results of tests conducted at $\Delta\varepsilon_t$ = 0.5% in air

Specimen[a]	Hold mode[b]	Cycles to failure N_f	Time to failure (h)	Strain ranges, %		Stress amplitude, MPa	
				Plastic, $\Delta\varepsilon_p$	Elastic, $\Delta\varepsilon_e$	Tensile, σ_t	Compressive, σ_c
			Tests conducted at 482°C				
MIL-44	0 h	51,656	36	0.25	0.25	206	261
MIL-27	0.1 h C	6,111	615	0.29	0.21	211	214
MIL-36	0.1 h T	20,147	2,039	0.29	0.21	202	215
BIL-24	0.1 h $\sigma = -0$	6,317	636	0.22	0.28	248	251
BIL-23	0.1 h $\sigma = +0$	15,557	1,567	0.27	0.23	200	211
BIL-25[c]	0.1 h $\sigma = -181$ MPa	11,667	1,167	0.25	0.25	210	226
BIL-27	0.1 h $\sigma = -0$[d]	7,443	745	0.26	0.24	210	220
BIL-28	0.1 h $\sigma = -0$[e]	7,527	767	0.26	0.24	217	217
BIL-30[c,f]	0.1 h $\sigma = +135$ MPa	>34,084	>3,431	0.27	0.27	194	227
			Tests conducted at 538°C				
MIL-10	0	16,036	11	0.28	0.22	192	199
MIL-12	0.1 h C	4,496	453	0.33	0.17	191	177
BIL-35	0.1 h $\sigma = -0$	5,680	572	0.31	0.19	177	159
BIL-29	0.25 h $T + C$	1,950	1,006	0.37	0.13	180	177
BIL-36	0.5 h $\sigma = -0$[b]	3,640	1,838	0.28	0.22	175	175
BIT-3	1.0 h $\sigma = -0$[b]	2,710	2,722	0.19	0.31	169	128
ITL-221	500 h T[g]	7,957	506	0.25	0.25	193	190

[a]Hourglass test specimen (6.35 mm minimum diameter with a radius-to-diameter ratio of 6.0); heat 3P5601.

[b]C = hold period introduced at peak compressive strain amplitude; T = hold period introduced at peak tensile strain amplitude; $\sigma = -0$ implies that the strain hold period was introduced near the point on the hysteresis loop where stress = 0 with corresponding compressive strain (tension-going); and $\sigma = +0$ implies that the hold period was introduced when stress = 0 with corresponding tensile strain (compresssion-going).

[c]Hold period at point on the hystersis loop where no relaxation occurs.

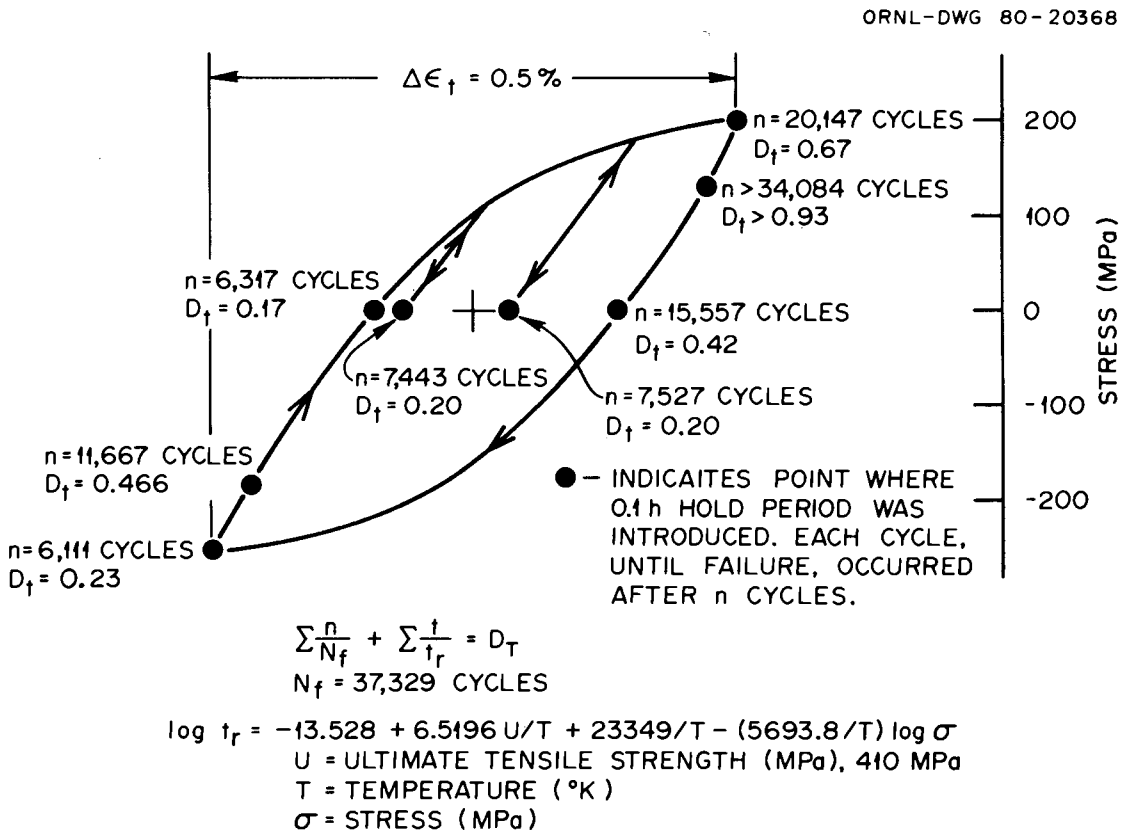
[d]During the tension-going portion on the hysteresis loop, the specimen was loaded to a tensile stress of 105 MPa then unloaded to stress = 0, where the strain hold period was introduced.

[e]The specimen is loaded to a tensile stress of 189 MPa then unloaded to stress = 0, where the strain hold period is introduced.

[f]Test discontinued with no indication of imminent failure of the specimen.

[g]The specimen was initially loaded to the peak tensile strain amplitude indicated during the first 1/4 cycle and a hold period introduced.

Results presented in Fig. 9 are given in terms of cycle life n and total damage sum, that is, classical creep and fatigue damage D_t. All the tests were run in strain control at a single strain range and temperature, with a hold period introduced in each cycle at a single point on the hysteresis



$$\Sigma \frac{n}{N_f} + \Sigma \frac{t}{t_r} = D_T$$

N_f = 37,329 CYCLES

$$\log t_r = -13.528 + 6.5196\, U/T + 23349/T - (5693.8/T) \log \sigma$$

U = ULTIMATE TENSILE STRENGTH (MPa), 410 MPa
T = TEMPERATURE (°K)
σ = STRESS (MPa)

Fig. 9. Time and cycle fraction damage analysis for annealed 2 1/4 Cr-1 Mo steel heat 3P5601 tested at 482°C in air.

loop. The duration of the hold period was either 0 or 0.1 h. Results of these tests conducted in air demonstrate the following for the particular strain range ($\Delta\varepsilon_t$ = 0.5%) and temperature (482°C):

1. Compression holds are more damaging than are tension holds of equal duration [6111 versus 20,147 cycles to failure (Figs. 10–12)].

2. In comparison with zero hold time or continuous-cycle tests, tests conducted with a hold period introduced at zero stress (Figs. 9, 13, and 14) show decreased fatigue life: the average cycle life for three specimens of this heat subjected to continuous cycling at a strain rate of 4×10^{-3}/s was 37,329 versus cycle lives of 6,317 and 15,557 for the zero stress points shown. Specimens BIL-27 and 28 were programmed to permit a stress overshoot before the 0.1-h hold period at zero stress, as shown in Figs. 15 and 16. This operation was done in an effort to determine if the tensile stress overshoot would improve cycle life by relief of residual

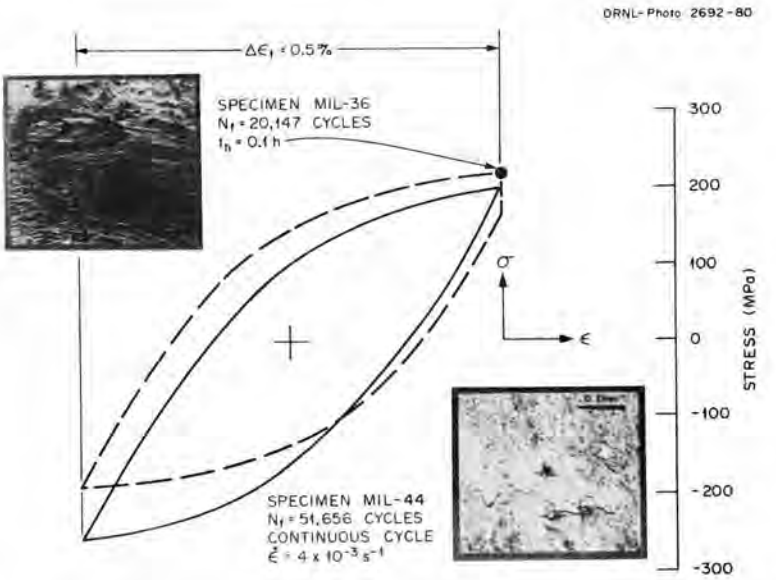


Fig. 10. Comparison of hysteresis loops, surfaces, and fatigue lives of two specimens subjected to strain-control cycling at 482°C. Note that specimen MIL-36 had a 0.1-h hold period introduced in each cycle at peak tensile strain.

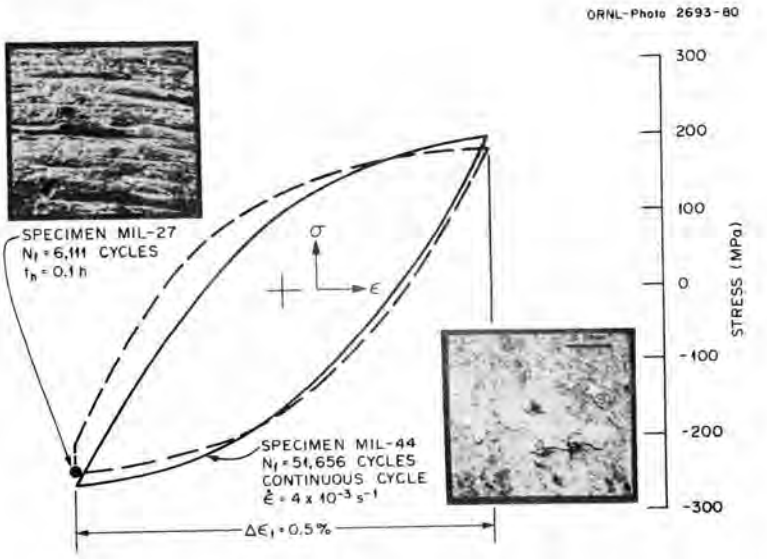


Fig. 11. Comparison of hysteresis loops, surfaces, and fatigue lives of two specimens subjected to strain-control cycling at 482°C. Note that specimen MIL-27 had a 0.1-h hold period introduced in each cycle at peak compressive strain.

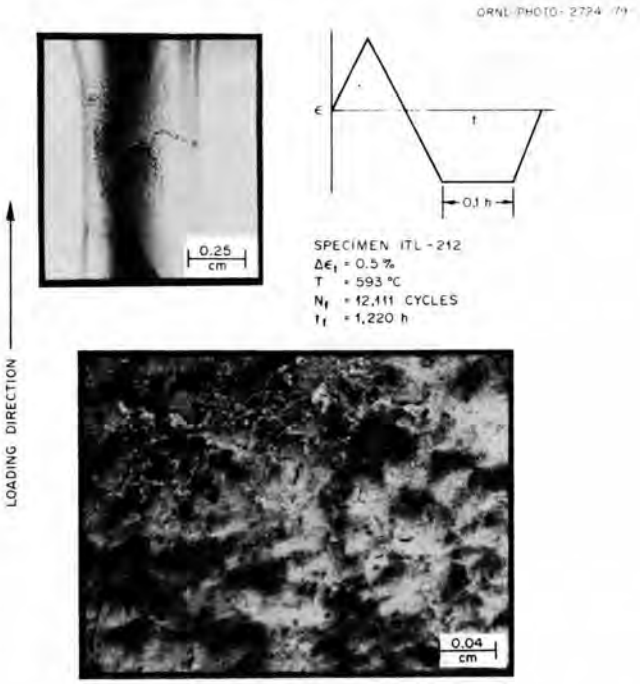


Fig. 12. The surface of a specimen of 2 1/4 Cr-1 Mo steel tested in impure helium in strain control with a compression hold period in each cycle.

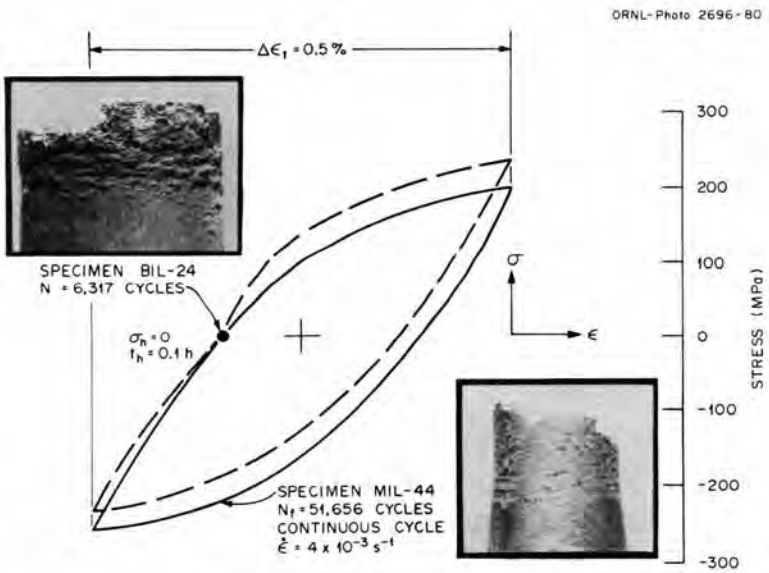


Fig. 13. Comparison of hysteresis loops, surfaces, and fatigue lives of two specimens subjected to strain-control cycling at 482°C. Note that specimen BIL-24 had a 0.1-h hold period introduced in each cycle at zero stress.

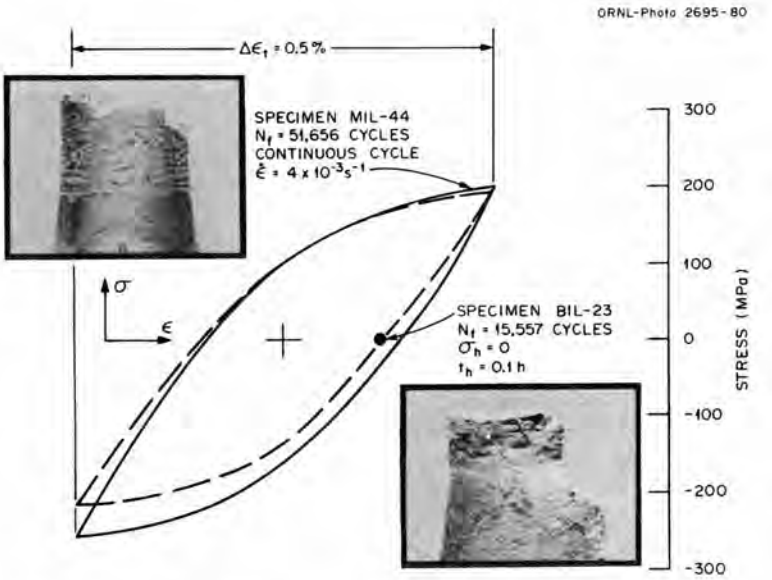


Fig. 14. Comparison of hysteresis loops, surfaces, and fatigue lives of two specimens subjected to strain-control cycling at 482°C. Note that specimen BIL-23 had a 0.1-h hold period introduced in each cycle at zero stress.

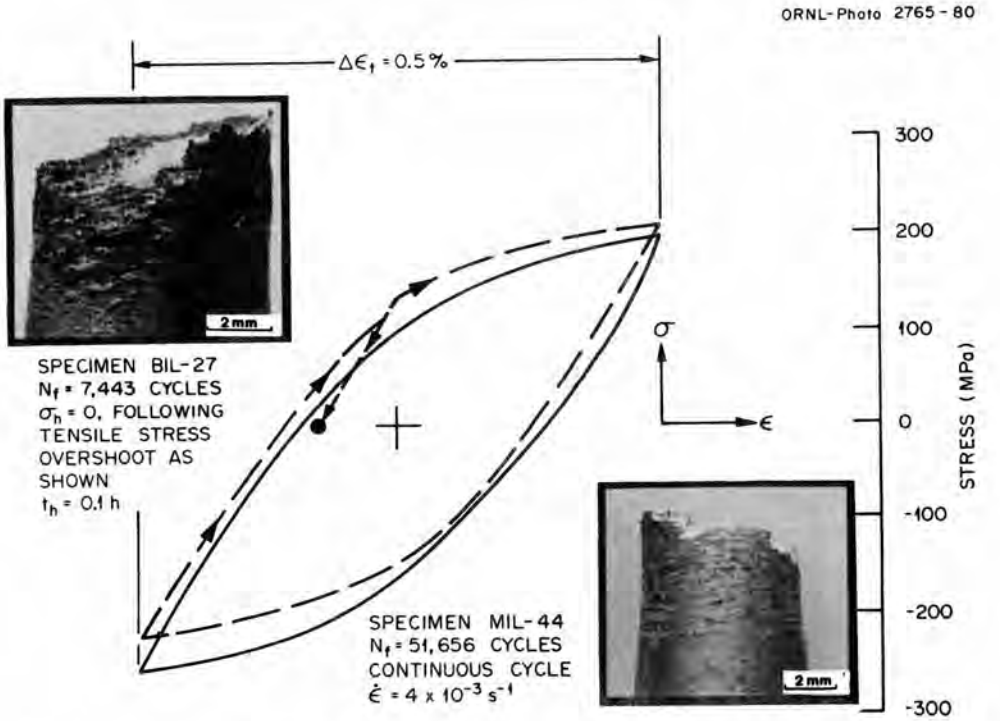


Fig. 15. Comparison of hysteresis loops, surfaces, and fatigue lives of two specimens subjected to strain-control cycling at 482°C. Note that specimen BIL-27 was subjected to a tensile stress overshoot before the 0.1-h hold time at zero stress.

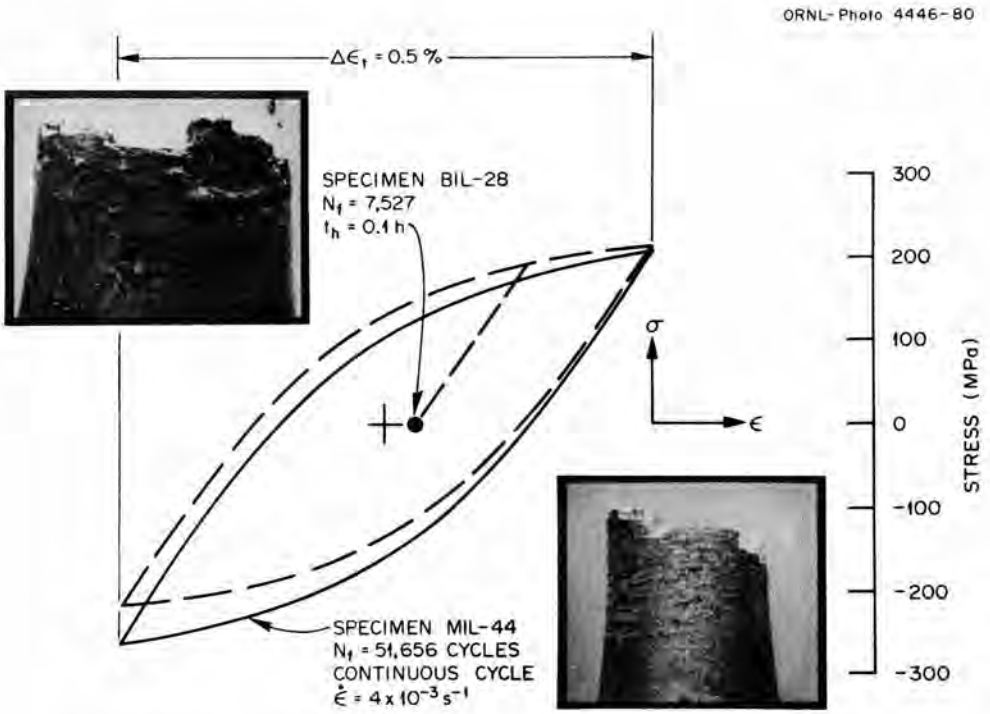


Fig. 16. Comparison of hysteresis loops, surfaces, and fatigue lives of two specimens subjected to strain-control cycling at 482°C. Note that specimen BIL-28 had a 0.1-h hold period introduced in each cycle at zero stress.

stress in the oxide or metal substrate. We examined the cycle lives of the zero stress hold time tests given in Fig. 9 and concluded that *all* such hold periods were damaging: cycle life was considerably less than the average continuous-cycle life. Further, tensile overstressing on the tension-going side of the hysteresis loop caused little or no change in the resultant number of cycles to failure. These effects are attributed to environment-waveform interactions, as shown by the oxide cracks in Figs. 13 through 16. The hold period on the tension-going side of the hysteresis loop is more damaging in terms of cycle life than that on the compression-going side of the loop, that is, 6317 versus 15,557 cycles to failure (Figs. 13 and 14). A similar finding has been reported for type 304 stainless steel.[10]

3. After continuous cycling at the indicated strain range, we located points on the hysteresis loop in both tension and compression where little or no stress relaxation occurred. The point in compression

was at approximately −181 MPa for the conditions indicated in Fig. 17, and the resultant fatigue life was 11,667 cycles to failure. This test again shows degradation in lifetime compared with the continuous-cycle life at these conditions (11,667 versus 37,329 cycles to failure).

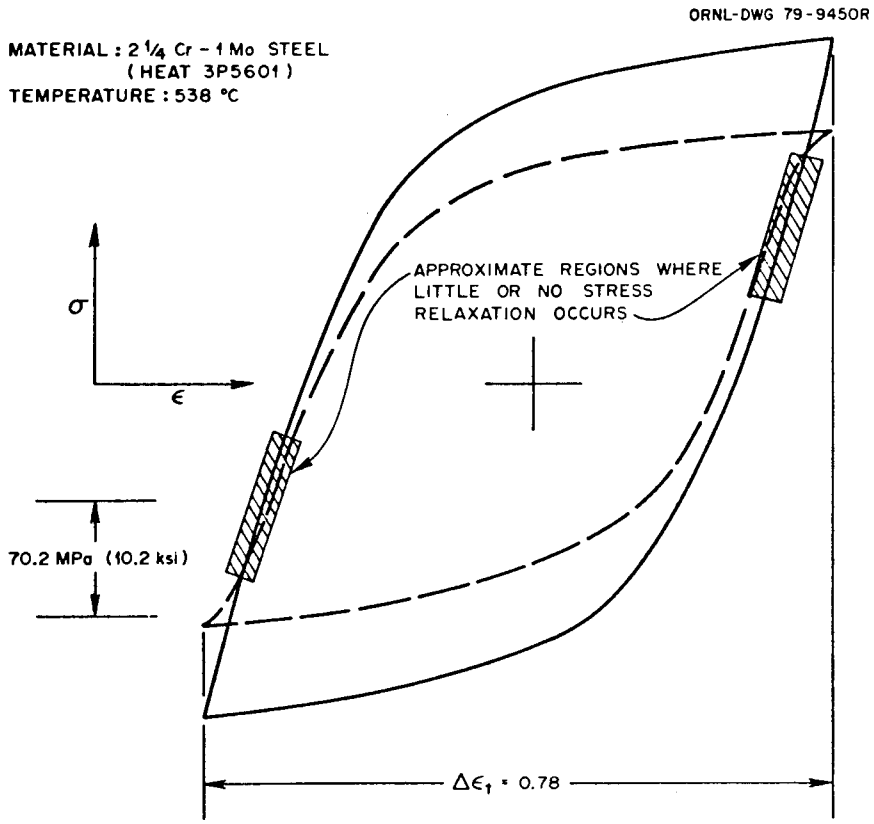


Fig. 17. Dashed lines represent the locus of stress relaxation points following 0.1-h strain hold periods from various positions on the solid curve. Intersecting points represent positions of zero stress relaxation.

Specimen BIL-30 was similarly cycled, with a 0.1-h hold period introduced in each cycle on the tension side of the loop (+135 MPa) where little or no relaxation occurred. In this case the test was discontinued before failure, with the cyclic life exceeding 34,084. Figure 18 shows the surface of specimen BIL-30 at the termination of the test. Note the lack of oxide cracking. These tests again demonstrate the strong waveform-environment interaction known to occur in this material.

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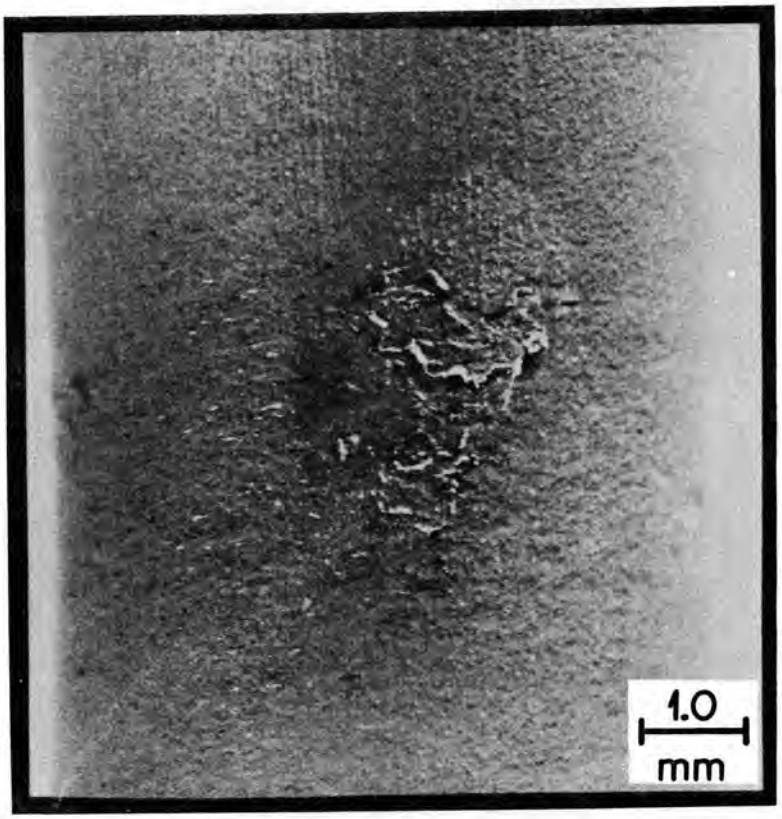

Fig. 18. Surface of specimen BIL-30 at the end of test. Note that the oxide has not cracked. Slight marking on surface is from extensometer contact. Tested with a total strain range of 0.5% and a 0.1-h hold at +135 MPa. Sample did not fail in 34,084 cycles and 3431 h.

4. A linear damage summation of time and cycle fractions has been performed on the various tests shown in Fig. 9. 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.

In addition to the tests conducted at 482°C and discussed above, two additional tests were conducted at 538°C. These tests (BIL-29 and BIL-36) were again conducted at a total strain range of 0.5%. The waveforms employed and results of these tests are described in Table 1. Specimen BIL-29 was tested with 0.25-h hold periods at both peak compression and tension strain in each cycle until failure (Fig. 19). The resultant

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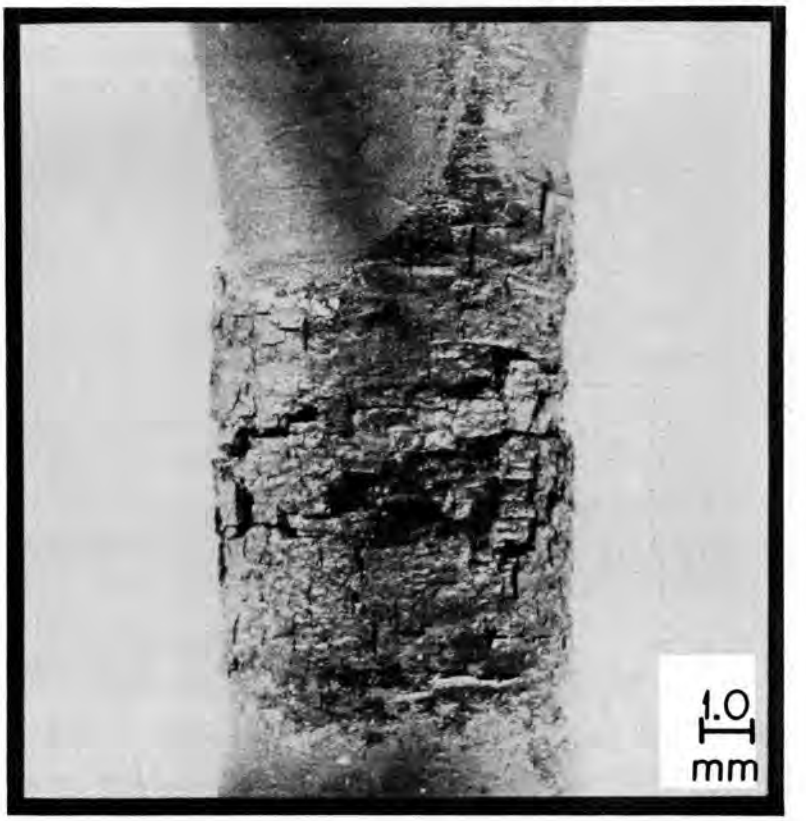

Fig. 19. Surface of specimen BIL-29 at the end of test. Note extensive oxide cracking on specimen surface. Tested at 482°C and a total strain range of 0.5%, with both tension and compression 0.25-h holds. Failed after 1950 cycles in 1006 h.

number of cycles to failure was 1950, indicating that this waveform was the most damaging to cycle life of any test conducted to date in this series. The second test (BIL-36) was at zero stress for a 0.5-h hold time. It was a sequel to that of specimen BIL-35 and was identical except that the hold period was 5 times as long. The objective of conducting this test was to determine if a continued degradation in cycle life occurred with increased duration of the hold period for this particular waveform. Specimen BIL-35 failed after 5680 cycles, and specimen BIL-36 (Fig. 20) failed after 3640 cycles, showing that an increase in the hold period further degrades life. The reader should also note that the average continuous-cycle life for this heat of material (3P5601) at this strain range is 22,000 cycles. Since the hold periods in both of these

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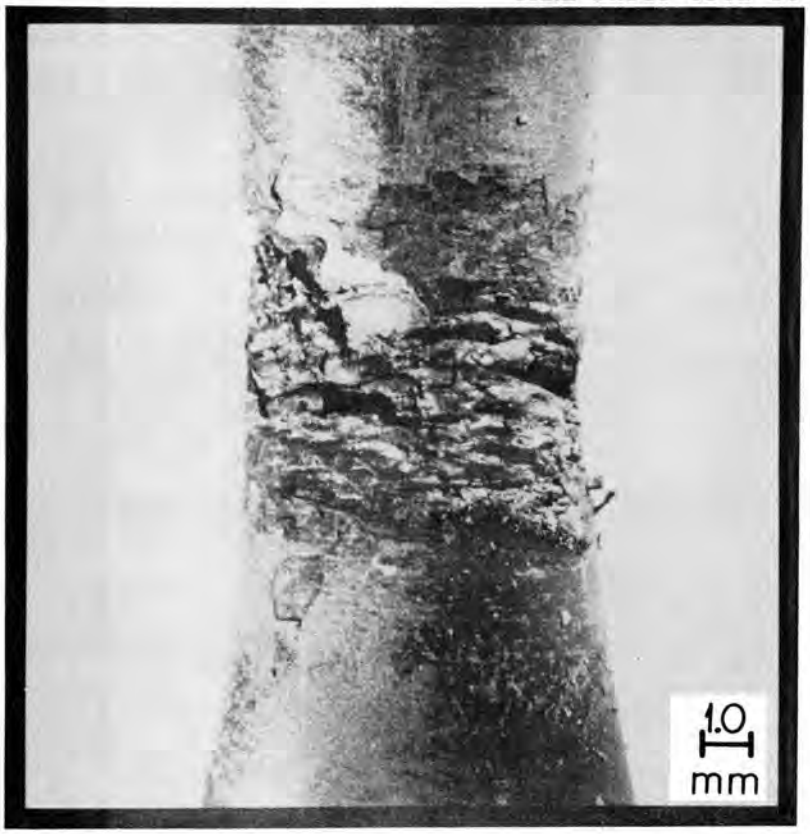

Fig. 20. Surface of specimen BIL-36 at the end of test. Note extensive cracking and surface deformation. Tested at 538°C and a total strain range of 0.5%, with 0.5-h hold at 0 stress, tension-going. Failed after 3640 cycles in 1838 h.

tests were conducted at zero stress, no classical creep damage t/t_r was incurred, yet, in the case of specimen BIL-36, the 0.5-h hold period reduced cycle life by a factor of 6. These results again confirm previous observations that a simple summation of time and cycle fractions to form a damage law is not adequate because of strong environmental interactions and resultant oxide cracking, which can initiate fatigue cracks and be particularly deleterious at certain strain ranges and imposed cyclic waveforms. We therefore conclude that this type of damage is not accounted for in a simple t/t_r or creep rupture damage summation approach.

Figure 21 is a plot of cycles to failure versus length of hold time for various waveforms imposed on specimens tested in strain control at 538°C and at a strain range of 0.5%. The plots show that a waveform with

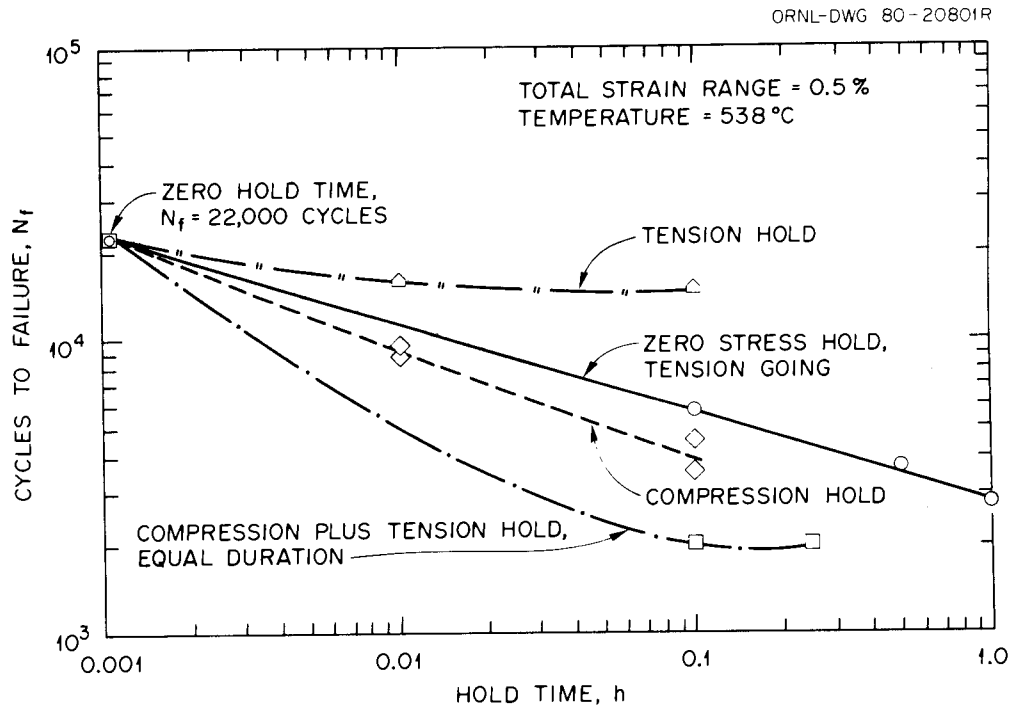

Fig. 21. Influence of waveform on the strain-controlled fatigue life of 2 1/4 Cr-1 Mo steel tested at 538°C and at a strain range of 0.5%.

both tension and compression hold periods of equal duration imposed in each cycle until failure is the most damaging form found to date.

Examination of the surfaces of specimens tested in air has shown that oxide interaction with the surface may produce characteristic circumferential markings, depending on the waveform imposed (Figs. 2 and 10, 11, 13, 16, and 18–20). These markings are thought to decrease the number of cycles required for crack initiation with resultant reduction in cyclic life.[3,4,6] The markings are absent from the surface of specimens tested in nonoxidizing environments (Figs. 2 and 12). The exact role of waveform in producing oxide cracking is not yet clear. It has been suggested,[4] for example, that compression holds produce oxides essentially at zero stress. When the specimen is subsequently cycled to tensile stress levels, the oxide cracks and initiates a fatigue crack. Tensile holds by this concept give the opposite effect: the oxide is more able to withstand subsequent compression loading and impedes or reduces oxide cracking. However, the explanation may not be that simple because the oxidation process itself is known to produce stresses in the range of 10^2 to 10^4 MPa in the growing

oxide scales of some metals.[11] The magnitude and sign (compression or tension) of the stress depends on many factors such as (1) oxide-to-metal volume ratio, (2) sample geometry,[12] (3) mode of diffusion within the oxide, (4) oxide morphology, (5) specimen surface finish, (6) and whether or not the oxide is single or multiphased (the case for 2 1/4 Cr-1 Mo steel oxidized in air). If the oxidation process itself produces stresses in the oxide, they may also be similarly introduced into the metal substrate. Such stresses might relax as a result of creep during hold periods, depending on the waveform imposed. The role of the oxidation process and waveform interaction is complicated, and is not completely understood at this time. A complete explanation of early crack initiation requires additional testing, both in air and in protective environments.

Examples of such tests with emphasis on testing in air effects are discussed in the following section of this report.

Future Work — Annealed 2 1/4 Cr-1 Mo

Results of the above tests suggest a number of questions about the time-dependent fatigue behavior of this material, such as:

1. Can the role of an oxidizing environment be quantified to permit model development that would be applicable to complex waveforms and states of stress? Typically, corrosion processes that form a protective or non-porous layer follow some form of parabolic reaction rate law. However, in the case of a corrosion fatigue process, a protective film may not be stable, depending on the particular cyclic waveform involved.
2. What is the strain range below which oxide cracking and resultant fatigue crack initiation do not occur, regardless of the waveform employed or the thickness of the oxide?
3. To what extent is classical creep damage (grain boundary voidage or cavitation) important in influencing the time-dependent fatigue behavior of this material for conditions appropriate to steam generator design?
4. To what extent does the oxidation process itself contribute to subsequent crack initiation (production of residual stresses in the metal substrate, which are subsequently relieved during elevated-temperature strain hold periods)?

5. Will mean stresses be more or less damaging in applications involving high-cycle fatigue?
6. Is Miner's rule appropriate for random loading situations?
7. What is the most damaging waveform that one can subject this material to; does continued degradation in cycle life occur with increased hold time?

In an attempt to answer some of the above questions, we formulated an initial test plan. Table 2 presents the test plan or matrix and gives details and status of the tests to be conducted in air. Similar tests must also be conducted in low-oxygen environments.

Table 2. Suggested additional creep-fatigue tests for 2 1/4 Cr-1 Mo steel[a]

Test	Temperature (°C)	Strain range (%)	Hold period (h) and mode[b]	Estimated time per test (h)	Priority
1	538	0.5	1 *C* — peak strain[c]	5,000	1
1a	538	0.5	1 — zero stress, compressive strain	5,000	1[d]
1b	538	0.5	1 *CT*	4,000	1[e]
2	482 or 538	0.5	1 *T* — peak strain[c]	15,000	1
3	482 or 538	0.5	0.1 *C*, 1000 cycles, then 0.1 *T*	500	1
4	482 or 538	0.5	0.1 *T*, 5000 cycles, then 0.1 *C*	1,000	1
5	482 or 538	0.5	500 *C*, 1 cycle, then 0.1 *C*	1,000	1
6	482 or 538	0.5	500 *C*, 1 cycle, then no hold	550	1
7	427	0.5	0.1 *T* — peak strain	2,000	2
8	427	0.5	0.1 *C* — peak strain	2,000	2
9	482 or 538	0.5	1 *CT* — peak strain	10,000	2
10	482 or 538	0.5	0.1 zero strain tensile stress	1,000	2
11	482 or 538	0.5	0.1 zero strain compressive stress	1,000	2
12	482	0.35	0.05 *CT* (repeat of MIL-72)	5,000	2
13	482	0.3	0.01 *C* (repeat of MIL-61)	5,000	2
14	482 or 538	0.5	Age in air (500–1000) then 0.1 *C*	500	2
15	482 or 538	0.5	Age in air (500–1000) then 0.1 *T*	1,000	2
16	482 or 538	0.5	Age in air (500–1000) then no hold	1,000	2
17	482 or 538	0.5	500 *C*, 1 cycle, then 0.1 *T*	1,000	2
18	427	1.0	0.01 *C* — peak strain	25	3
19	427	1.0	0.01 *T* — peak strain	25	3
20	427	1.0	0.1 *T* — peak strain	250	3
21	482 or 538	0.5	500 *T*, 1 cycle, then 0.1 *C*	1,000	3
22	482 or 538	0.5	500 *T*, 1 cycle, then no hold	550	3[d]
23	482 or 538	0.5	500 *T*, 1 cycle, then 0.1 *T*	1,500	3

[a]In addition longer time, lower strain data are needed in very low oxygen environments. The results of these tests are expected to affect both the priorities and nature of subsequent tests; this list is only a starting point.

[b]*C* = a hold period at peak compression, and *T* = a hold period at peak tension on the hysteresis loop.

[c]Even longer hold times would be desirable, within the constraints of test time.

[d]Tests completed.

[e]Tests still in progress.

Modified 9 Cr-1 Mo Steel*

Exploratory continuous-cycle and time-dependent creep-fatigue tests are currently under way on modified* 9 Cr-1 Mo steel. Figure 22 is a plot of continuous-cycle data obtained to date at several temperatures and presented in Tables 3 and 4. Data are compared with similar information derived by Wood, Baldwin, and Williamson[13] on standard 9 Cr-1 Mo steel. Available data suggest that modified 9 Cr-1 Mo has superior fatigue resistance compared with standard 9 Cr-1 Mo steel, particularly in the high-cycle range.

Table 5 lists all data generated to date at 538°C. Figure 23 compares the resultant continuous-cycle fatigue curve with curves for other

*C = 0.08/0.12, Mn = 0.30/0.60, P = 0.2 max, S = 0.10 max, Si = 0.20/0.50, Cr = 8.0/9.5, Mo = 0.85/1.05, V = 0.18/0.25, Cb = 0.06/0.1, N = 0.03/0.07, Ni = 0.20 max, Al = 0.04 max, compositions (%).

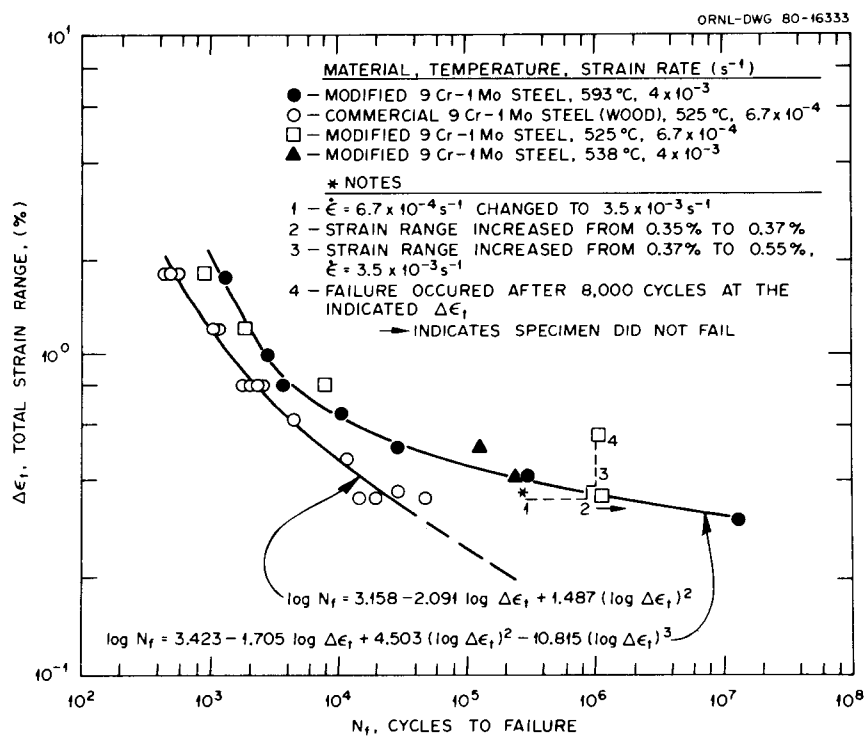

Fig. 22. Improved high-cycle fatigue properties occur in modified 9 Cr-1 Mo steel. Both commercial and modified materials are normalized and tempered. Data on modified 9 Cr-1 Mo steel at 593°C is by courtesy of G. E. Korth, Idaho National Engineering Laboratory.

Table 3. Strain-control fatigue data[a] on modified 9 Cr-1 Mo steel[b] at 593°C

Specimen	Total strain range, $\Delta\varepsilon_t$ (%)	Hold time and mode (h)	Stress amplitude,[c] MPa		Stress range, $\Delta\sigma$ (MPa)	Strain range,[c] %		Relaxed stress, σ_r (MPa)	Cycles to failure, N_f	Time to failure, t_f (h)
			Tensile, σ_t	Compressive, σ_c		Elastic, $\Delta\varepsilon_e$	Plastic, $\Delta\varepsilon_p$			
72T	1.00	None	223	238	461	0.32	0.68		7,432	10.30
73T	0.50	None	184	195	379	0.27	0.23		110,377	81.25
74T	0.45	None	176	188	364	0.26	0.19		139,477	86.50
30T[d]	1.75	None	262	243	505	0.22	1.53		1,303	3.13
26T[d]	1.01	None	254	291	545	0.32	0.69		2,818	3.87
27T[d]	0.81	None	245	275	520	0.31	0.50		3,726	4.13
31T[d]	0.65	None	208	189	397	0.24	0.41		10,916	5.93
28T[d]	0.51	None	210	199	409	0.25	0.26		29,136	20.02
32T[d]	0.41	None	140	155	295	0.18	0.23		299,707	164.75
29T[d,e]	0.30	None	143	119	262	0.16	0.14		11,800,000	513.95
34T[e]	1.00	0.1T[f]	227	283	510	0.18	0.82	71	1,584	160.60
36T[e]	1.00	0.1C[g]	182	186	368	0.19	0.81	35	1,190	119.67

[a]Fully reversed push-pull axial fatigue ($R = -1$); strain control and triangular waveform with strain rate = 4×10^{-3}/s; and hourglass-shaped specimens radius/diameter = 6 and 5.08 mm minimum diameter.

[b]Heat 91887, normalized (1038°C) and tempered (760°C).

[c]$N_f/2$ properties.

[d]Data generated is by courtesy of G. E. Korth, Idaho National Engineering Laboratory.

[e]Changed to load control at 1,000,000 strain-control cycles (413.95 h), cycled at 30 Hz with sine waveform in load control until failure at ±131 MPa.

[f]T = a hold period at peak tension on the hysteresis loop.

[g]C = a hold period at peak compression.

Table 4. Strain-control fatigue data[a] on modified 9 Cr-1 Mo steel[b] at 525°C

Specimen	Total strain range, $\Delta\varepsilon_t$ (%)	Stress amplitude,[c] MPa		Stress range, $\Delta\sigma$ (MPa)	Strain range,[c] %		Cycles to failure, N_f	Time to failure, t_f (h)
		Tensile, σ_t	Compressive, σ_c		Elastic, $\Delta\varepsilon_e$	Plastic, $\Delta\varepsilon_p$		
40T[d]	0.35	186	205	391	0.23	0.12	1,033,075	1,243.0
41T	0.35	189	201	390	0.22	0.13	>1,158,498	>1,307.3[e]
38T	1.20	285	296	581	0.34	0.86	1,824	18.2
37T	1.82	294	321	615	0.36	1.46	910	13.8
39T	0.80	257	278	536	0.32	0.48	7,853	52.4

[a]Fully reversed push-pull axial fatigue ($R = -1$), strain control and triangular waveform with strain rate = 6.7×10^{-4}/s; and hourglass-shaped specimens radius/diameter = 6 and 5.08 mm minimum diameter. No hold and no relaxed stress.

[b]Heat 91887, normalized (1038°C) and tempered (760°C).

[c]$N_f/2$ properties.

[d]Part 1 $\dot{\varepsilon} = 6.7 \times 10^{-4}$/s from start to 281,946 cycles.
Part 2 $\dot{\varepsilon} \geq 3.5 \times 10^{-3}$/s from 281,946 cycles to 852,720 cycles.
Part 3 $\dot{\varepsilon} \geq 3.5 \times 10^{-3}$/s, $\Delta\varepsilon_e = 0.37\%$, 852,720 to 1,025,070 cycles.
Part 4 $\dot{\varepsilon} \geq 3.5 \times 10^{-3}$/s, $\Delta\varepsilon_e = 0.55\%$, 1,025,070 to 1,033,075 cycles.

[e]Test terminated before failure.

Table 5. Strain control fatigue data on modified 9 Cr-1 Mo steel at 538°C

Heat	Specimen[a,b]	Total strain range,[c] $\Delta\varepsilon_t$ (%)	Hold time and mode[d] (h)	Stress amplitude,[e] MPa		Stress range, $\Delta\sigma$ (MPa)	Strain range,[e,f] %		Relaxed stress, σ_r (MPa)	Cycles to failure, N_f	Time to failure, t_f (h)
				Tensile, σ_t	Compressive, σ_c		Elastic, $\Delta\varepsilon_e$	Plastic, $\Delta\varepsilon_p$			
91887	58T	1.00	None	274	286	560	0.36	0.64		2,951	4.10
91887	46T	0.51	None	272	286	558	0.37	0.14		22,316	15.50
91887	68T	0.50	None	238	241	479	0.31	0.19		25,775	17.89
91887	53T	0.50	0.01T	193	241	434	0.26	0.24	159	>40,911[g]	>437.10[g]
91887	50T	0.50	0.01C	231	224	455	0.28	0.22	200	12,368	132.10
91887	52T	0.50	0.10C	241	200	441	0.26	0.24	162	9,917	998.50
91887	57T	0.50	$0.10\sigma = -0$[h]	241	238	479	0.31	0.19	0	8,135	817.00
91887	48T	0.40	None	210	224	434	0.28	0.12		260,770	144.90
30182	182E4T	1.00	None	279	286	565	0.37	0.63		2,907	4.04
30182	182E2T	0.50	None	283	307	590	0.38	0.12		5,708	3.96
30182	182E3T	0.40	None	224	243	467	0.30	0.10		62,227	34.57
30182	176-52T	0.40	None	232	265	497	0.32	0.07		52,129	29.00
30182	176-53T	0.30	None	183	283	466	0.25	0.05		4,456,920	
30394	394C4T	1.00	None	305	314	619	0.40	0.60		3,827	5.31
30394	394C3T	0.50	None	259	262	521	0.34	0.16		52,400	36.39
30394	394E60T	0.50	0.25C	272	203	475	0.26	0.24	134	8,840	2,216.14
30394	394C2T	0.40	None	241	241	482	0.31	0.09		382,381	192.90
30394	394E59T	0.40	None	234	307	541	0.35	0.10		218,889	121.61

[a]Hourglass specimen, 5.08 mm minimum diameter with a radius-to-minimum-diameter ratio of 6.

[b]Product form was 25-mm-thick plate except for specimens 394C2T–4T, which were from 232-mm-diam bar. Material normalized (1038°C) and tempered (760°C).

[c]Fully reversed, continuous-cycle strain-controlled fatigue tests were conducted by employing a triangular waveform at a constant strain rate, $\dot{\varepsilon} = 4 \times 10^{-3}$/s.

[d]Test in progress.

[e]$N_f/2$ properties.

[f]Calculated values using Young's modulus E of 154 GPa; $\Delta\varepsilon_e = \Delta\sigma/E$, and $\Delta\varepsilon_p = \Delta\varepsilon_t - \Delta\sigma/E$.

[g]Test terminated before failure.

[h]$\sigma = -0$ means that the strain hold period was introduced near the point on the hysteresis loop where the stress is approximately zero on the tension-going side of the hysteresis loop.

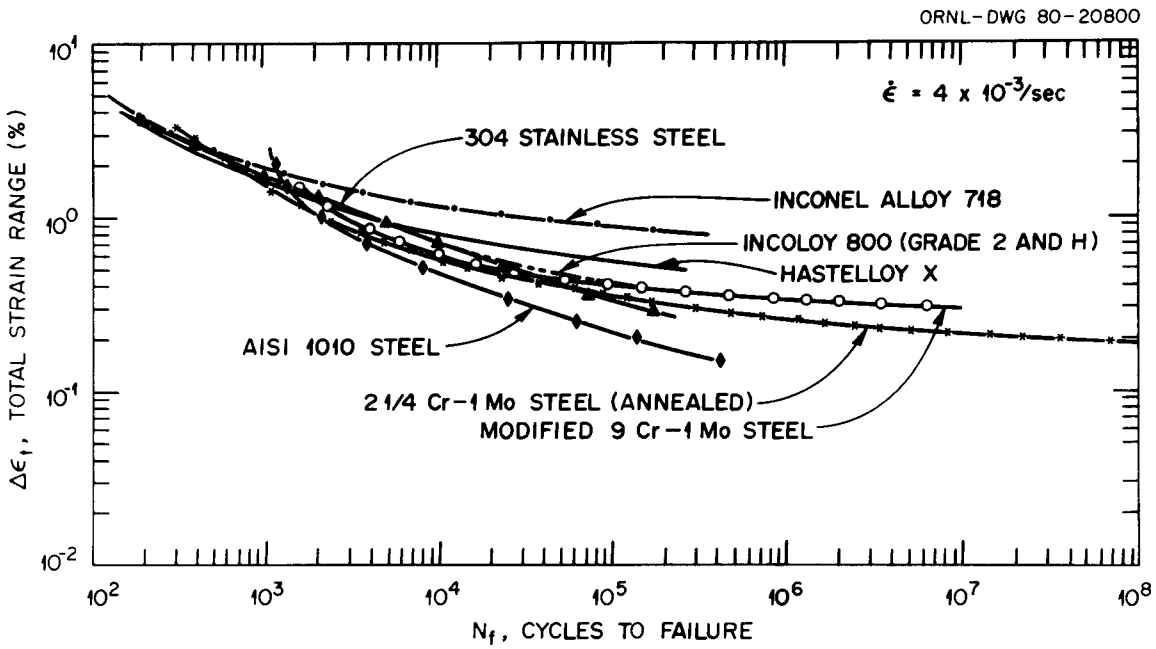

Fig. 23. Comparison of the fatigue behavior of several materials at 538°C (1000°F). Lines represent best-fit values of actual data. Data for type 304 stainless steel include tests conducted at 538°C (1000°F) and 566°C (1050°F).

structural alloys at 538°C. The high-cycle fatigue resistance of modified 9 Cr-1 Mo steel is superior to that of annealed 2 1/4 Cr-1 Mo steel.

Tables 3 and 5 show that limited time-dependent or exploratory fatigue test data are available from strain-controlled fully reversed testing. The time-dependent or hold-time fatigue data given in Table 5 show:

1. Short tensile hold periods are not damaging in terms of reducing fatigue life at this temperature (compare results of specimen 53T with results from continuous-cycling tests, i.e. 46T and 68T).

2. Compressive hold periods are damaging; the reduction in cycle life is proportional to the length of hold time imposed (compare results of specimens 50T, 52T, and 60T).

3. A single zero-stress hold time test (57T) was conducted with a 0.1-h hold on the tension-going side of the hysteresis loop. The resultant number of cycles to failure was 8135 compared with 25,775 for another specimen (68T) subjected to continuous cycling at this same strain range. Thus, from preliminary tests conducted on this material, we

conclude that the time-dependent fatigue behavior in air is similar to that of 2 1/4 Cr-1 Mo steel, although this material does not oxidize as much as does 2 1/4 Cr-1 Mo steel at elevated temperatures.

Figures 24 and 25 show the surface of specimens 52T and 60T tested in air. Note the lack of visible oxide or surface bulging or cracking.

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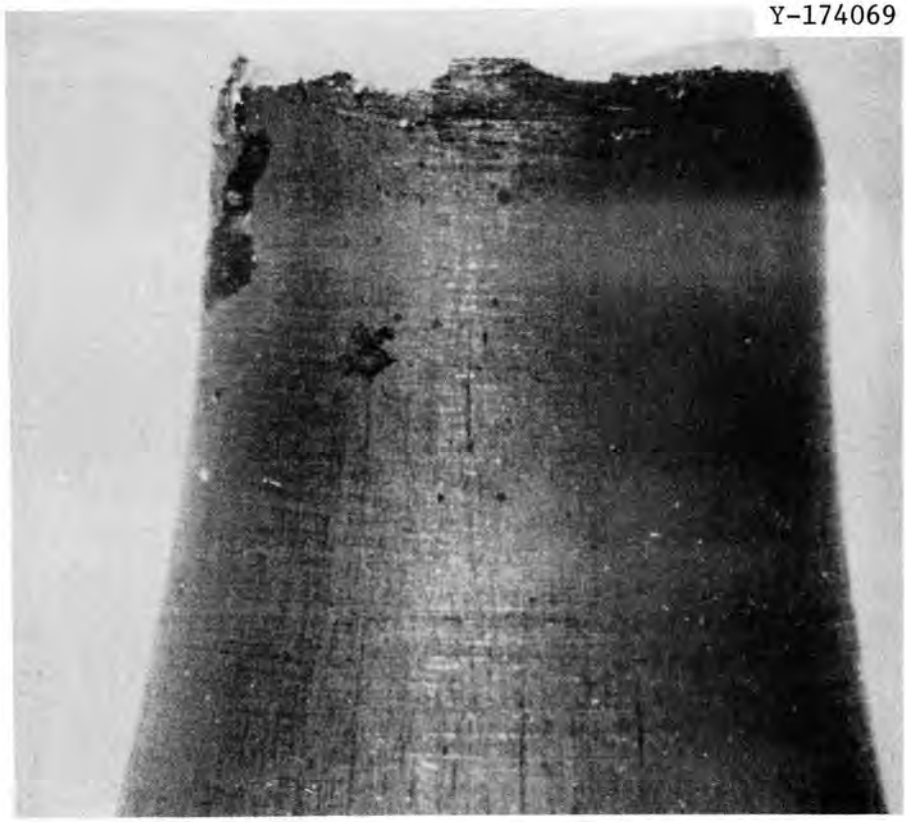

Fig. 24. Surface of specimen 52T. Note the absence of visible oxide or surface cracking. Modified 9 Cr-1 Mo tested at 538°C and a 0.5% total strain range with a 0.1-h compressive hold. Failed after 9917 cycles in 999 h.

Specimen 52T was subjected to the same waveform as MIL-27 (2 1/4 Cr-1 Mo steel), whose surface is shown in Fig. 11, except that the modified 9 Cr-1 Mo test was at 538°C rather than 482°C. Figure 26 shows the microstructure adjacent to the fracture surface of specimen 52T. Note the lack of grain boundary voidage.

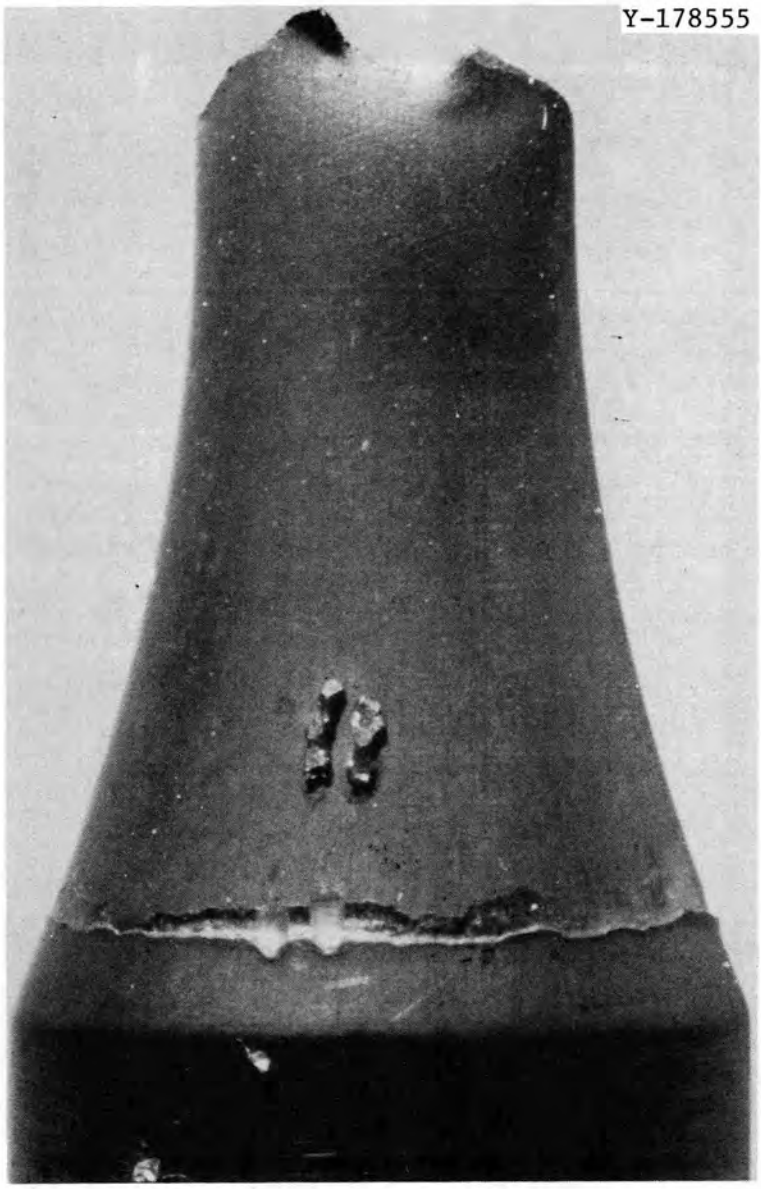

Fig. 25. Surface of specimen 60T. Note the absence of visible oxide or surface cracking. Modified 9 Cr-1 Mo tested at 538°C and 0.5% total strain range with a 0.25 h compression hold failed after 8,840 cycles.

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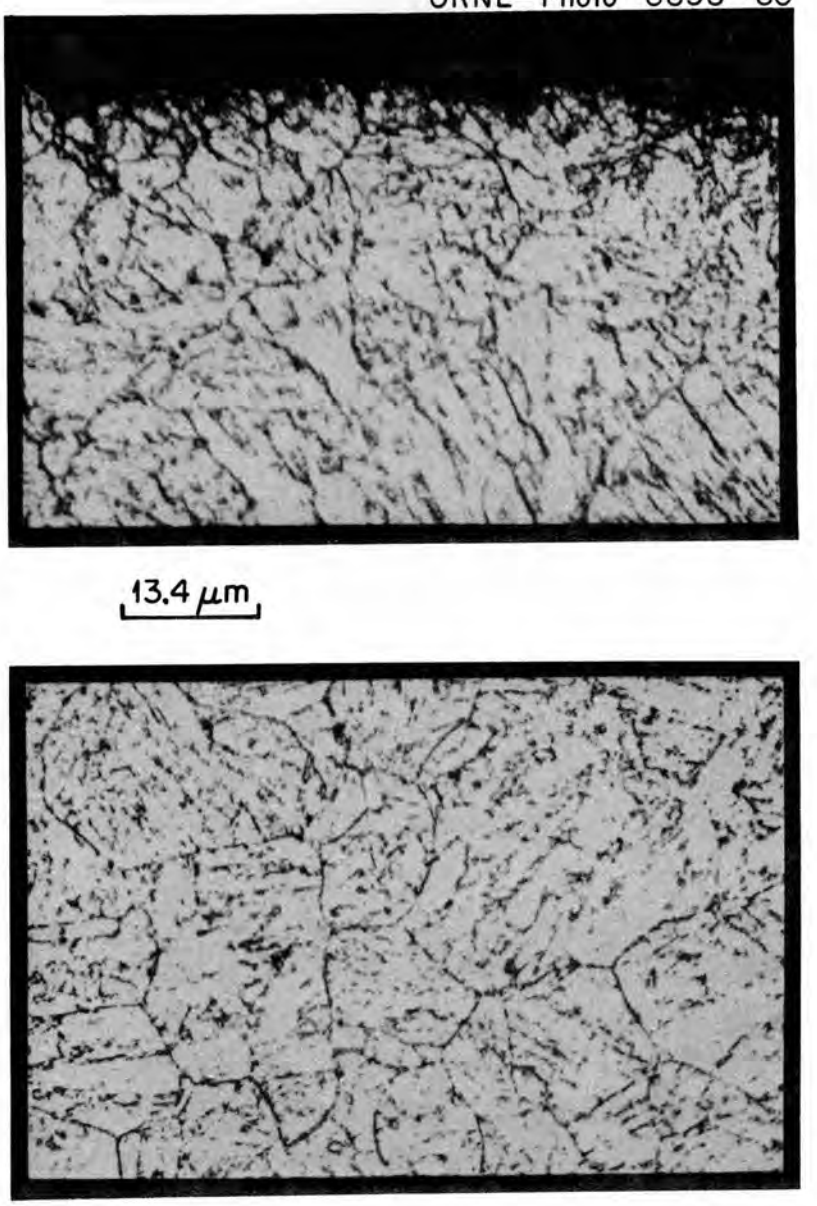

Fig. 26. Microstructure adjacent to the fracture surface of specimen 52T. Note the absence of grain boundary voidage.

SUMMARY AND CONCLUSIONS

Recently reported results from a number of ongoing materials programs were reviewed. These programs are aimed at determining the influence of temperature, time, waveform, and environment on the elevated-temperature fatigue properties of 2 1/4 Cr-1 Mo steel and modified 9 Cr-1 Mo steel. We reached the following conclusions from tests conducted in air:

1. At temperatures ranging from about 371 to 482°C, tensile and fatigue properties of annealed 2 1/4 Cr-1 Mo steel depend on testing strain rate, or waveform, primarily because of the effects of dynamic strain aging or interaction solid-solution hardening.

2. Compression hold periods are more damaging than tension hold periods of equivalent duration, particularly at low strain ranges, for both 2 1/4 Cr-1 Mo and modified 9 Cr-1 Mo steel. These effects do not occur in inert environments, that is, nonoxidizing environments (at least for annealed 2 1/4 Cr-1 Mo steel), where tension hold periods are more damaging than are compression holds.

3. Hold periods introduced at zero stress are damaging in reducing cycle life and are particularly deleterious when they occur on the tension-going side of the hysteresis loop for 2 1/4 Cr-1 Mo steel. Limited data suggest a similar conclusion for modified 9 Cr-1 Mo steel.

4. Overall, hold periods introduced on the tension-going side of the hysteresis loop at various positions are more damaging to cycle life than are those at corresponding positions on the commpression-going side of the loop in 2 1/4 Cr-1 Mo steel. These waveform effects were attributed to environmental interaction with resultant decreased resistance to crack initiation in 2 1/4 Cr-1 Mo steel.

5. Damage sum values D_t as calculated by simple linear damage summation for 2 1/4 Cr-1 Mo steel do not tend toward a unique value. The D_t values obtained depend on waveform. It should be noted, however, that, although the damage sums given (Fig. 9) are the those of the total creep and fatigue damage fractions, most of the damage is from fatigue; for example, specimen BIL-30 (which did not fail after 3431 h of testing) had a calculated total damage sum D_t of 0.93, but the creep damage was only 0.02. The low calculated creep damage values are a result of the fairly low test temperature, stress level, and duration of hold period employed.

6. Comparisons of continuous-cycle fatigue data for standard 9 Cr-1 Mo with modified 9 Cr-1 Mo steel show the latter to have superior fatigue properties, particularly in the high-cycle range.

7. Comparisons of the high-cycle fatigue life of modified 9 Cr-1 Mo steel with several other structural alloys at 538°C show this alloy to be superior to annealed 2 1/4 Cr-1 Mo steel and inferior to alloy 718.

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