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Abstract

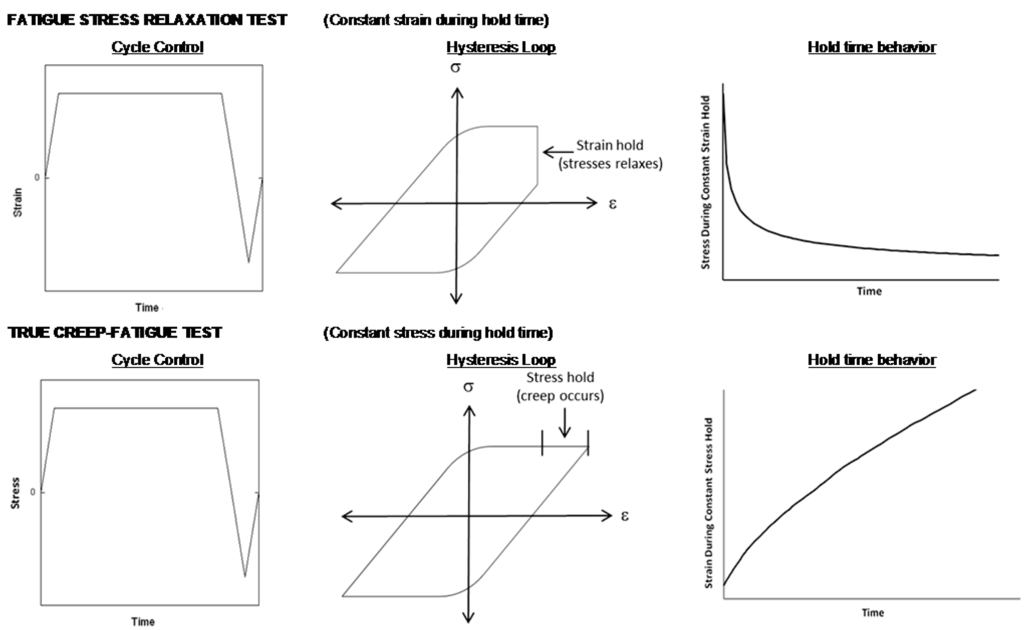
It is well known in energy systems that the creep lifetime of high temperature alloys is significantly degraded when a cyclic load is superimposed on components operating in the creep regime. A test method has been developed in an attempt to characterize creep-fatigue behavior of alloys at high temperature. The test imposes a hold time during the tensile phase of a fully reversed strain-controlled low cycle fatigue test. Stress relaxation occurs during the strain-controlled hold period. This type of fatigue stress relaxation test tends to emphasize the fatigue portion of the total damage and does not necessarily represent the behavior of a component in-service well. Several different approaches to laboratory testing of creep-fatigue at 950°C have been investigated for Alloy 617, the primary candidate for application in VHTR heat exchangers. The potential for mode switching in a cyclic test from strain control to load control, to allow specimen extension by creep, has been investigated to further emphasize the creep damage. In addition, tests with a lower strain rate during loading have been conducted to examine the influence of creep damage occurring during loading. Very short constant strain hold time tests have also been conducted to examine the influence of the rapid stress relaxation that occurs at the beginning of strain holds.

Introduction

Creep-fatigue deformation is a combination of creep damage and fatigue damage and is expected to be the primary damage mode for a Very High Temperature Reactor (VHTR) intermediate heat exchanger (IHX). Transients during start up and shut down produce cyclic loadings, while the stresses relax during steady power operation inducing creep damage. Material that experiences creep-fatigue deformation fails more quickly than material experiencing only creep or fatigue. Therefore, creep-fatigue testing is critical to incorporating a material in the ASME Code for design of nuclear systems. Furthermore, it is important to understand the individual contributions of creep damage and fatigue damage to creep-fatigue failure modes. A variety of experiments have been designed to discern the relative contributions of creep and fatigue to creep-fatigue behaviour at 950°C, the maximum temperature of interest for the VHTR application.

Alloy 617 is the leading candidate for the VHTR IHX and testing is ongoing to generate data so it can be incorporated into the ASME Boiler and Pressure Vessel Code, Section III, Subsection NH for elevated temperature nuclear system design. [1] Creep-fatigue testing (strain-controlled fatigue with a hold time at the peak tensile strain) has been performed in a laboratory setting to reproduce the expected damage mode, as well as continuous low cycle fatigue (LCF) testing (i.e., no hold time) to provide a baseline for the creep-fatigue behavior. [2, 3, 4, 5] This creep-fatigue testing is henceforth referred to as fatigue stress relaxation (FSR) testing since the amount of "creep" deformation that is calculated is a result of stress relaxation rather than conventional tensile creep deformation. Alternative testing using a load-controlled tensile hold has been developed for ferritic-martensitic steel. [6] This type of test has been called a true creep-fatigue test since the creep portion of the deformation occurs in a manner that is similar to a uniaxial creep test. Load-control testing also offers the potential to provide test conditions that are creep dominated, whereas FSR tests are fatigue dominated because stress relaxation is very rapid in Alloy 617 at high temperatures. These two types of creep-fatigue tests are compared in Figure 1.

Figure 1. Schematic diagrams comparing control mode and specimen response for two types of creep-fatigue testing.



An alternative to the conventional FSR test was designed to study the influence of the loading cycle at slow loading conditions more representative of in-service component loading. At the high temperatures that are being investigated for Alloy 617, it cannot be assumed that creep deformation occurs only during the hold time and not during loading. Decoupling of the creep from the plasticity components during loading is important for constitutive modelling. Furthermore, it is known that Alloy 617 is strain rate sensitive at elevated temperatures and thus the stresses achieved during cycling are lower at lower strain rates, thereby influencing the amount of creep damage during each cycle.

Finally, tests with only a 2 s hold time were performed. Since stress relaxation occurs very rapidly during the hold, these tests help illuminate the impact of the stress relaxation by minimizing the time for this to occur and comparing results to the LCF results.

Experimental Procedure

All testing was conducted at 950°C with fully reversed cyclic loading.

Load-Control Tests

Two tests were executed entirely in load control using a loading rate of 1120 N/s, and a target load of ±1767N, corresponding to about 40MPa. One test had a 30 second tension load hold and one had a 30 minute hold. The stress histories for these two tests are shown in the first column of the first two rows of Figure 2. Both of these tests were conducted in two steps as the total strain experienced by the specimen was greater than the strain range of the extensometer. Tests were suspended, the extensometer was reset, and the tests were restarted and run to a total strain of nearly 40%, rather than to failure.

An additional test was designed to demonstrate true creep-fatigue with a stress during the hold of approximately 72 MPa. The specimen was held until a target tensile strain of 0.3% was achieved, rather than holding for a given time as described above. The procedure alternated between strain-control and load-control modes to achieve this result. The cycle started in strain control, applying a tensile strain at a rate of 10^{-3} /s until a load was reached corresponding to the target stress. At that point the specimen was allowed to creep in load control to the target tensile strain value, at which point the cycle was completed in strain control by imposing a compressive strain of -0.3% and then reversing to tension until the target stress is reached again. The stress and strain histories for this test are shown in the third row of plots of Figure 2. Cycling continued until the specimen cracked. Once cracking occurred the tension load criteria could no longer be met and the test effectively became a LCF test with a strain range of ±0.3% strain.

Strain Rate Variations

A low strain rate FSR test was conducted such that its total cycle time was equal to that of the typical test conditions. The typical strain rate is 10^{-3} /s and for a hold time of 600 s, the total cycle time is 606 s. By using a combination of a strain rate of 10^{-4} /s and a hold time of 546 s, the total cycle time is maintained at 606 s. In addition, a test was run at a strain rate of 10^{-5} /s with a hold time of 600 s. For this strain rate, it was not possible to have the same total cycle time and maintain significant hold times. In all cases the total strain range was 0.3%. The strain histories of the slower strain rate tests are compared to that of a standard 600 s hold time test in Figure 3.

Short Hold Tests

FSR tests were conducted to 0.3% and 1.0% total strain with a 2 sec constant strain hold time at peak tensile strain. The strain rate was the nominal 10^{-3} /s value used in the baseline LCF and FSR tests.

Figure 2. Stress and strain histories and stress-strain hysteresis loops from a mid-life cycle for the three tests performed in load control.

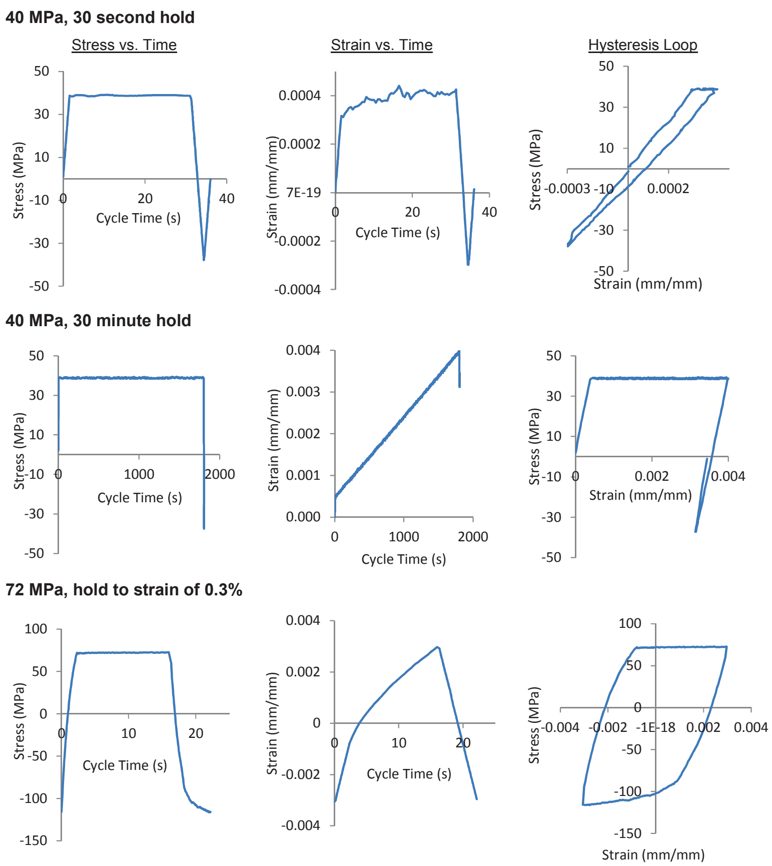
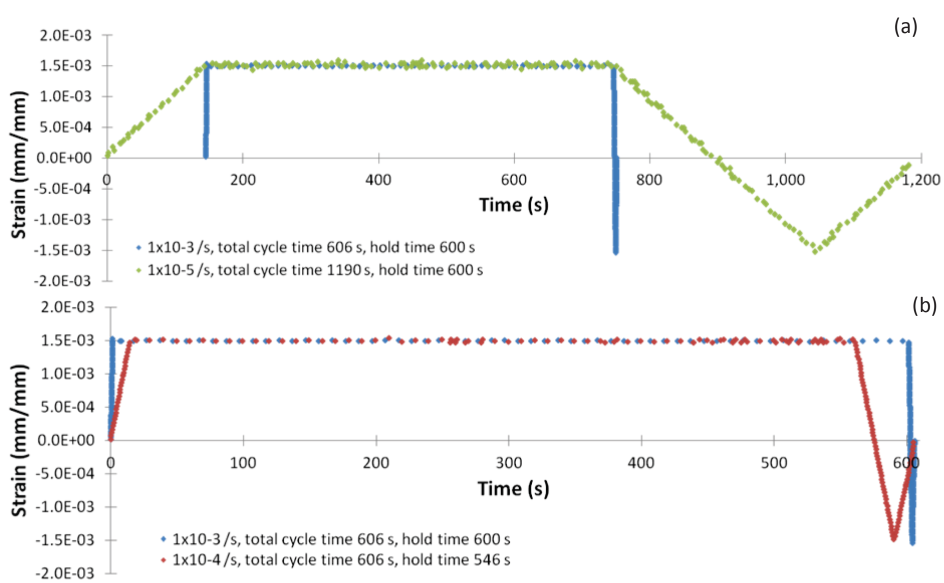


Figure 3. Strain histories of tests run at different strain rates, illustrating (a) a constant total cycle time and (b) a constant hold time.



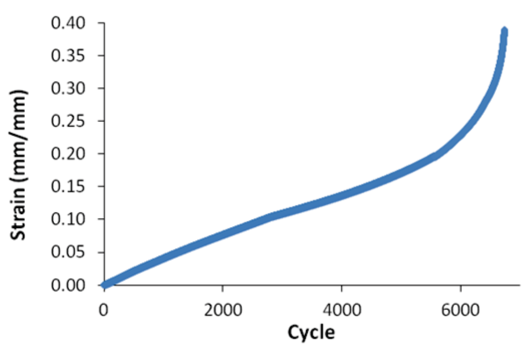
Results

Load-Control Tests

The stress-strain hysteresis loops, stress control history and strain response history for both types of load-control tests are presented in Figure 2. The first two rows of plots in Figure 2 are from the constant hold time tests. For the 30 s hold test, most of the strain occurs during loading, while for the 30 minute test, most of the strain occurs via creep during the hold. The hysteresis loops do not resemble the schematic loops of typical creep-fatigue tests shown in Figure 1. Specimens accumulate strain as the tests progress, rather than alternating between controlled strain limits, as is the case for both FSR testing and for the true creep-fatigue test discussed below. The strain accumulation as a function of cycle is shown in Figure 4 for the 30 s hold test. The figure strongly resembles a curve from a traditional creep test for Alloy 617. The rapid strain rate at the end of the test indicates failure was imminent, i.e. even significant additional creep strain would only result in a few additional cycles, and final cycle can be used as an approximation of cycles to failure.

The last row of plots in Figure 2 is from the true creep-fatigue test. The strain accumulates quickly during the tensile hold and most of the inelastic strain accumulated each cycle occurs during the hold. The stress history is not linear during loading, because that portion of the test is done in strain control (the strain history is linear in this region). The hysteresis loop shown in Figure 2 resembles the schematic of the true creep-fatigue test shown in Figure 1, although the proportion of strain accumulated during the hold is larger.

Figure 4. Accumulated strain as a function of cycle for load-controlled creep-fatigue test of Alloy 617 at 950ºC with 30 second hold time at 40MPa.



Test conditions and results from the load-controlled creep-fatigue tests are listed in Table 1. The sum of the hold time is calculated as the hold time at a mid-cycle multiplied by the cycles to failure. This value can be compared to the creep rupture time, determined for a 950°C creep test at the tensile hold stress, using a Larson-Miller plot (creep stress vs. the Larson-Miller Parameter which is a function of both time to rupture and test temperature) for a large database of Alloy 617 creep tests. In all cases the sum of the hold time is less than the creep rupture time, illustrating the influence of fatigue damage.

Similarly, the maximum cycle (or cycles to failure) of the creep-fatigue test can be compared to the fatigue life for a 950°C LCF test with the same total strain range, estimated from a total strain range, $\Delta\varepsilon_T$, vs. cycles to failure plot of a database of fatigue tests. A $\%\Delta\varepsilon_T$ of 0.07

appears to be below the fatigue endurance limit, estimated as about 0.15% from the database. Note the database does not go below this level, and it is not known if Alloy 617 actually has an endurance limit at this temperature. In any case, the lifetime is much greater than 10^6 cycles. For both of the time-hold tests, the maximum cycle is much less than the fatigue life, indicating a large influence of creep damage in these tests. The cycles to failure for the strain-hold test is about the same as the fatigue life estimate under similar conditions.

Table 1. Comparison of load-controlled creep-fatigue test lives to creep and fatigue life for similar conditions. Estimates are calculated from stress-strain behavior of a mid-life cycle.

hold type	σ_{hold} (MPa)	% $\Delta\varepsilon_T$	% $\Delta\varepsilon_{in}$ [1]	t_{hold} (s)	sum t_{hold} (h)	creep $t_{rupture}$ [2] (h)	cycles[3]	fatigue life [4] (cycles)
time	40	0.07	0.0085	30	58	242	7000	NA[5]
time	40	0.40	0.343	1800	35	242	70	2939
strain	72	0.60	0.446	14[6]	6	9	1560	1328

[1] inelastic strain - width of hysteresis loop at zero stress
[2] creep rupture time estimated from Larson-Miller plot for Alloy 617
[3] cycles to failure for strain hold test, cycle at end of test for time hold tests, a reasonable proximity to failure as strain was increasing rapidly with each cycle at end of test.
[4] fatigue life estimated from 950°C fatigue data for Alloy 617
[5] total strain appears to below the fatigue endurance limit
[6] hold time varies significantly with cycle

Strain Rate Variations

Figure 5 shows hysteresis loops from a midlife cycle for tests run at strain rates spanning two orders of magnitude. The number of cycles to failure observed for the test run at 10^{-4} /s was within the scatter of the creep-fatigue tests with the faster strain rate of 10^{-3} /s and a hold time of 600 s, as shown in Figure 6.

Figure 5. Hysteresis loops from a midlife cycle for tests run at three different strain rates.

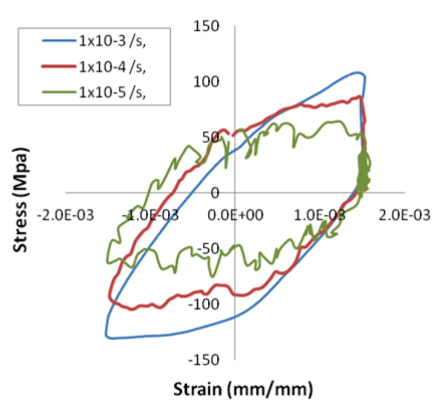
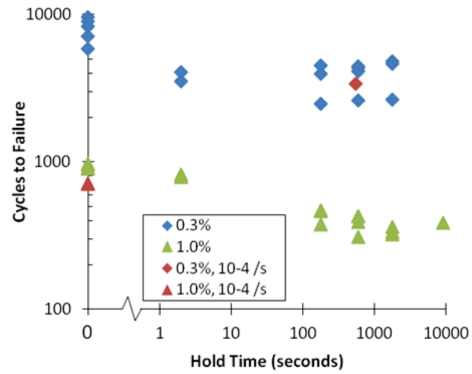


Figure 6. Plot of the cycles to failure as a function of hold time for Alloy 617 in fatigue and creep-fatigue at 950ºC for total strain ranges of 0.3 and 1.0%.

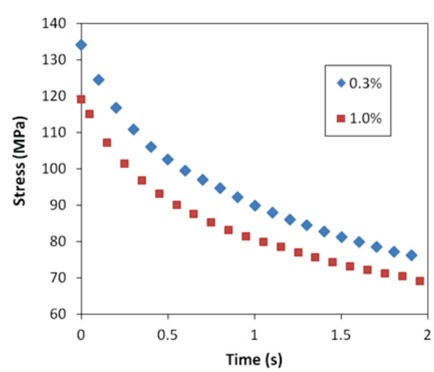


Short Hold Tests

The data from the FSR tests with 2 second hold times are included in Figure 6. The number of cycles to failure was similar to the longer hold time tests (600 sec and 1800 sec) at the lower strain range (0.3% total strain) and significantly less than in pure fatigue. At the 1.0% total strain range, the number of cycles to failure was slightly lower than in fatigue but, in this case, higher than the longer hold time tests.

Rapid stress relaxation occurs in Alloy 617 within 2 seconds and is shown for the midlife 0.3% and 1.0% total strain hysteresis loop in Figure 7. The stress drops over 50 MPa during the 2 second hold, a short time relative to creep deformation. Interestingly, cyclic softening behavior is similar to pure LCF for a given total strain range.

Figure 7. Stress relaxation curves during 2 second hold at mid-life cycle.



Discussion

Creep-Fatigue Interaction Diagram

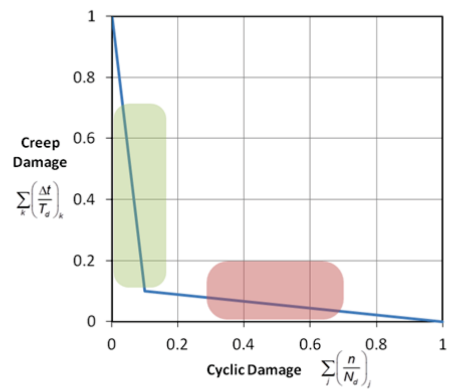
In the ASME Boiler and Pressure Vessel Code, Section III, Subsection NH, [1] creep-fatigue life is evaluated by a linear summation of fractions of cyclic damage and creep damage. The creep-fatigue criterion is given by:

$$\underbrace{\sum_j \left(\frac{n}{N_d}\right)_j}_{\text{Cyclic Damage}} + \underbrace{\sum_k \left(\frac{\Delta t}{T_d}\right)_k}_{\text{Creep Damage}} \leq D \qquad (1)$$

where n and N_d are the number of cycles of type j and the allowable number of cycles of the same cycle type, respectively; and Δt and T_d are the actual time at stress level k and the allowable time at that stress level, respectively; D is the allowable combined damage fraction. The cyclic and creep damage terms on the left-hand side of Equation

(1) are evaluated in an uncoupled manner, and the interaction of creep and fatigue is accounted for empirically by the D term on the right side of the equation. This can be represented graphically by the creep-fatigue interaction diagram, also known as a damage diagram (d-diagram). The d-diagram proposed in the Draft Alloy 617 Code Case [7] is shown in Figure 8.

Figure 8. Example of a D-diagram for Alloy 617. with intersection coordinates of (0.1, 0.1). Red shading indicates location of experimental data from FSR testing and green shading indicates the predicted range for load-controlled testing.



Preliminary analysis of the available Alloy 617 FSR data obtained from tests in air at 950°C supports the fatigue-dominant region of the bilinear creep-fatigue interaction. The data gathered to date for strain ranges of 0.3 to 2.0 and hold times of 0-30 minutes all fall within the red shading on Figure 8. Efforts to generate creep-fatigue data in the creep-dominant region of the d-diagram using smaller strain ranges and/or longer hold times have been explored and it appears FSR testing cannot populate the creep-significant portion of the d-diagram. The rapid stress relaxation of Alloy 617 observed during the tensile hold limits the amount of creep damage, regardless of test conditions chosen.

It appears a different approach is necessary to fully characterize the creep dominated region of the diagram. Load-controlled creep-fatigue testing enables the rapid accumulation of creep strain during the tensile hold, as the stress is not able to relax, and makes possible experimental conditions that are creep-dominated. Preliminary analysis indicates that data is expected to fall within the green shaded area.

Coffin-Manson Relationship

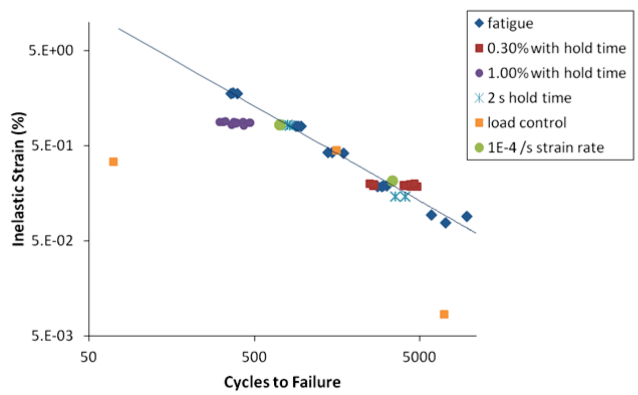
The Coffin-Manson fatigue relationship [8, 9] illustrates that fatigue cycles to failure is a function of inelastic strain (indicated by the width of the hysteresis loop). The Coffin-Manson plot for Alloy 617 is shown in Figure 9. The blue diamonds and line represent the LCF data and a fit to this data.

It has been previously shown [5, 4] that the number of cycles to failure at the 0.3% strain range follow the Coffin-Manson relationship, as shown in Figure 4. This is also the case for the 2 sec hold FSR tests with both 0.3 and 1.0 total strain ranges. However, for the 1.0% total strain FSR tests with longer hold times, the behavior does not follow the Coffin-Manson fatigue relationship, indicating a greater contribution from creep/stress relaxation. This is similar to the behavior shown in Figure 6, where the 1.0% 2 s hold FSR test is more similar to the 1.0% LCF tests than to the 1.0% FSR tests with longer hold times.

The 10^{-3} /s strain rate FSR test, as well as some 10^{-3} /s strain-rate LCF tests, fall on the same Coffin-Manson line as the bulk of the LCF tests run at 10^{-3} /s. It appears that the creep/stress-relaxation that occurs during the slower loading rate does not significantly impact the life of the material.

The load-controlled strain hold (true creep-fatigue) test falls on the Coffin-Manson line. Although this test was designed to allow significant creep to occur, both the inelastic strain (as determined by width of the hysteresis loop at mid-cycle) and the cycles to failure are similar to LCF tests with the same total strain range. Both load-controlled time-hold tests fall well below the line.

Figure 9. Coffin-Manson plot showing data from a variety of LCF and creep-fatigue tests.



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