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THE EFFECTS OF MEAN TENSILE STRESSES ON HIGH-CYCLE FATIGUE LIFE AND STRAIN ACCUMULATION IN SOME REACTOR MATERIALS

P. SOO AND J.G.Y. CHOW

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HTGR SAFETY EVALUATION DIVISION
DEPARTMENT OF APPLIED SCIENCE
BROOKHAVEN NATIONAL LABORATORY
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TABLE OF CONTENTS

Section	Page
Abstract	v
List of Tables	vi
List of Figures	vii
1. Introduction	1
2. Materials and Test Procedures	2
3. Effects of Mean Stress on High-Cycle Fatigue	3
3.1 Type 304 Stainless Steel Data	3
3.2 Normalized and Tempered 2½Cr-1Mo Steel Data	8
3.3 Incoloy-80CH Data	9
4. Strain Accumulation During Test	11
5. Metallographic Evaluation of Failure Mechanisms	14
6. Discussion and Conclusions	18
Acknowledgements	20
References	21

ABSTRACT

An assessment has been made of the effects of mean tensile stresses on the high-cycle fatigue behavior of solution-treated Type 304 stainless steel, normalized and tempered 2½Cr-1Mo steel, Incoloy-800H, and low-carbon Incoloy-800. Mean stresses are usually detrimental to fatigue strength, especially at high temperatures and stress levels, where significant creep can occur during fatigue cycling. Depending on the magnitudes of the alternating and mean stresses, failure may be creep or fatigue controlled. Strain accumulation is also affected by these stress levels and possibly, also, by the cyclic work-hardening characteristics of the material. It is shown that the Goodman Law for estimating mean stress effects is inadequate, since it does not account for time-dependent deformation. An alternative expression not having such a limitation was, therefore, derived and this relates the alternating and mean stresses to the time to failure. Based on limited metallographic observations of fatigue striations in the 2½Cr-1Mo steel an estimate was made of the crack propagation rate. It was found that a crack of critical size could, under certain conditions, propagate through most of the specimen diameter in a matter of seconds. This presents a more significant safety problem than the case for a crack extending under low-cycle conditions since preventative measures probably could not be implemented before the crack had grown to a large size.

LIST OF TABLES

	Page
Table 1 Chemistries of High-Cycle Fatigue Test Materials	22
Table 2 High-Cycle Mean-Stress Fatigue Data for Solution-Treated Type 304 Stainless Steel	23
Table 3 Stress-Rupture Data for Type 304 Stainless Steel, Incoloy-800H and Normalized and Tempered 2½Cr-1Mo Steel	25
Table 4 High-Cycle Mean-Stress Fatigue Data for Normalized and Tempered 2½Cr-1Mo Steel	26
Table 5 High-Cycle Mean-Stress Fatigue Data for Incoloy-800 and Incoloy-800H	27
Table 6 Dimensional Changes in Structural Materials During High-Cycle, Load-Controlled, Fully-Reversible Fatigue Testing	28
Table 7 Tensile Strain Accumulation in Unfailed, High-Cycle Mean-Stress Fatigue Samples	29

LIST OF FIGURES

		Page
Figure 1	Microstructures of High-Cycle Fatigue Test Materials.	30
Figure 2	Specimen Configurations for Fatigue and Stress-Rupture Testing.	31
Figure 3	Effect of a Mean Tensile Stress on the High-Cycle Fatigue of Solution-Treated Type 304 Stainless Steel at 72°F.	31
Figure 4	Effect of a Mean Tensile Stress on the High-Cycle Fatigue of Solution-Treated Type 304 Stainless Steel at 1100°F.	32
Figure 5	Goodman Diagram for Solution-Treated Type 304 Stainless Steel at 72°F.	32
Figure 6	Goodman Diagram for Solution-Treated Type 304 Stainless Steel at 1100°F.	33
Figure 7	Effect of Mean Stress on the Fatigue Hysteresis Loop.	33
Figure 8	Isochronous Mean Stress Fatigue Curves for Solution-Treated Type 304 Stainless Steel at 1100°F.	34
Figure 9	Relationship Between the Alternating and Mean Stresses for the High-Cycle Fatigue of Type 304 Stainless Steel at 1100°F.	34
Figure 10	Comparison of Calculated and Experimental Isochronous Mean-Stress High-Cycle Fatigue Curves for Solution-Treated Type 304 Stainless Steel at 1100°F.	34
Figure 11	Effect of a Mean Tensile Stress on the High-Cycle Fatigue of Normalized and Tempered 2½Cr-1Mo Steel at 1000°F.	34

Figure 12	Goodman Diagram for Normalized and Tempered 2½Cr-1Mo Steel at 1000°F.	35
Figure 13	Isochronous Mean Stress Fatigue Curves for Normalized and Tempered 2½Cr-1Mo Steel at 1000°F.	35
Figure 14	Relationship Between the Alternating and Mean Stresses for the High-Cycle Fatigue of Normalized and Tempered 2½Cr-1Mo Steel at 1000°F.	35
Figure 15	Values of σ_0 for Normalized and Tempered 2½Cr-1Mo Steel Mean-Stress High-Cycle Fatigue Data at 1000°F.	36
Figure 16	Comparison of Calculated and Experimental Isochronous Mean-Stress High-Cycle Fatigue Curves for Normalized and Tempered 2½Cr-1Mo Steel at 1000°F.	36
Figure 17	Effect of a Mean Tensile Stress on the High-Cycle Fatigue of Incoloy-800H at 1100°F.	36
Figure 18	Goodman Diagram for Incoloy-800H at 1100°F.	37
Figure 19	Isochronous Mean-Stress Fatigue Curves for Incoloy-800H at 1100°F.	37
Figure 20	Values of C for Incoloy-800H Mean-Stress High-Cycle Fatigue Data at 1100°F.	38
Figure 21	Comparison of Calculated and Experimental Mean-Stress High-Cycle Fatigue Curves for Incoloy-800H at 1100°F.	38
Figure 22	Effects of Mean Stress on the High-Cycle Fatigue of Solution-Treated Low-Carbon Incoloy-800 at 1200°F.	39
Figure 23	Goodman Diagram for Low-Carbon Incoloy-800 at 1200°F.	39
Figure 24	Strain Accumulation in Solution-Treated Type 304	40

Stainless Steel Under Mean-Stress High-Cycle Fatigue Conditions.

Figure 25	Strain Accumulation in Normalized and Tempered 2½Cr-1Mo Steel at 1000°F Under Mean-Stress High-Cycle Fatigue Conditions.	41
Figure 26	Strain Accumulation in Incoloy-800H Under Mean-Stress High-Cycle Fatigue Conditions at 1100°F.	41
Figure 27	Strain Accumulation in Low-Carbon Incoloy-800 Under Mean-Stress High-Cycle Fatigue Conditions	41
Figure 28	Effect of Fatigue Cycling on Stress Rupture Life.	42
Figure 29	Fractography of Solution-Treated Type 304 Stainless Steel Mean-Stress High-Cycle Fatigue Specimens at 1100°F.	43
Figure 30	Fractography of Incoloy-800H at 1100°F.	44
Figure 31	Fractography of Normalized and Tempered 2½Cr-1Mo Steel at 1000°F.	45
Figure 32(a)	Morphology of Fracture in Solution-Treated Type 304 Stainless Steel Mean-Stress High-Cycle Fatigue Specimens at 1100°F.	46
Figure 32(b)	Morphology of Fracture in Solution-Treated Type 304 Stainless Steel Mean-Stress High-Cycle Fatigue Specimens at 1100°F.	47
Figure 33(a)	Morphology of Fracture in Incoloy-800H Mean-Stress High-Cycle Fatigue Specimens at 1100°F.	48

Figure 33(b) Morphology of Fracture in Incoloy-800H Mean-Stress High-Cycle Fatigue Specimens at 1100 ⁰ F.	49
Figure 34(a) Morphology of Fracture in Normalized and Tempered 2¼Cr-1Mo Steel Mean-Stress High-Cycle Fatigue Specimens at 1000 ⁰ F.	50
Figure 34(b) Morphology of Fracture in Normalized and Tempered 2¼Cr-1Mo Steel Mean-Stress High-Cycle Fatigue Specimens at 1000 ⁰ F.	51

1. Introduction

High-cycle fatigue data are urgently needed in the field of nuclear technology for the evaluation of structural integrity in reactor components which are subjected to high-frequency cyclic loads. At the present time, such information is relatively sparse for materials and test conditions of interest. Some preliminary studies, however, have been conducted at Brookhaven National Laboratory (BNL) for fully-reversible deformation; i.e. the test specimens are stressed between equal tensile and compressive loads.¹⁻³ Although this loading state is relevant to some reactor structures, it usually represents an ideal situation since most components operate under a mean stress upon which is superimposed a cyclic load. Typical examples are vibrating heat exchanger tubes which are subjected to a mean stress caused by bending, and turbine blades and discs which are simultaneously subjected to vibrational stresses and mean stresses from centrifugal forces.

This work was initiated to determine how mean tensile stresses affect the high-cycle fatigue life of various reactor materials, so that safety-related structural analyses may be conducted on selected components. Emphasis was placed on high-temperature studies, for a wide range of mean stress values, so that the role of creep on the fatigue process could be evaluated*.

*Some of the data reported here were generated on a prior program.⁴

2. Materials and Test Procedures

Most of the materials evaluated here are of direct relevance to the High-Temperature Gas-Cooled, Gas-Cooled Fast Breeder, and Liquid-Metal Fast Breeder Reactor concepts. They include Incoloy-800H, solution-treated Type 304 stainless steel, and normalized and tempered 2½Cr-1Mo steel. A limited amount of work was also conducted on a low-carbon heat of Incoloy-800.

Table 1 gives the chemical analyses of the materials, and Figure 1 shows representative microstructures. Figure 2 shows the geometry of the test samples. For virtually all of the fatigue tests, the 1/8-inch diameter hourglass specimen was used. In the case of the Incoloy-800H tests, however, the supply of samples was depleted and several tests were run on larger 1/4-inch diameter samples prepared from a new heat of material (Heat HH7427A). All specimens were machined from heat-treated bar stock, and left in the surface-ground condition. In order to more clearly delineate the role of creep, a series of stress-rupture tests was conducted. For the Type 304 stainless steel the standard 1/8-inch fatigue specimen was utilized. For all other tests the parallel-sided specimens used were similar to those used previously for ultrasonic fatigue studies.¹⁻³ A comparison with data from the open literature showed that the specimen geometry did not noticeably influence the stress-rupture times.

All fatigue testing was performed on MTS Systems Corporation closed-loop, electrohydraulic machines, operating under load control in the push-pull mode at a frequency of 40 Hz. A sinusoidal load waveform was used with the initial stroke in the tensile direction. During the initiation

move from fatigue-controlled to creep-controlled failure.

An important point to note in Figure 4 is that the data pertain only to a cycling frequency of 40 Hz. Although changes in cycling rate will not greatly alter the relationship between the alternating stress and cycles-to-failure (N_f),¹⁻³ the time-to-failure (t_f) is affected since it is inversely proportional to the frequency. Therefore, if the rate of cycling is changed from, say, 40 to 4 Hz, the t_f values in Figure 4 will each have to be increased by a factor of 10. Hence, slow rates of cycling, which prolong the duration of a test, also tend to increase the amount of creep deformation.

In order to analytically evaluate the effects of mean stress on fatigue life, an approach developed by Goodman was initially investigated.⁵ In the "Goodman" diagram (Figures 5 and 6) the applied stress range on the sample is plotted against the mean tensile stress. The maximum and minimum stress lines are drawn so that they pass through both the ultimate tensile strength value for the material and the fatigue limit for fully-reversible deformation ($\sigma_m = 0$). According to Goodman's theory, these lines represent the boundaries between failure and non-failure conditions. For a range of materials at ambient temperatures the Goodman analysis has been used with success. Although the limited BNL results for 720°F (Figure 5) are in accordance with the procedure, the 1100°F data (Figure 6) show instances where the Goodman theory is inadequate. Many specimens failed within the "safe" triangular area of the diagram, especially for high applied mean stress levels where significant creep is occurring. Note that data points lying along the mean stress line are from stress-rupture

of a test the load was increased from zero to the required value. Limit switches were set so that deviations greater than 1 percent caused the test to terminate. The test temperature was maintained by a resistance-type furnace, which was controlled to approximately $\pm 2^{\circ}\text{F}$.

3. Effects of Mean Stress on High-Cycle Fatigue

Throughout this work the term "mean stress" will be used, although it is recognized that the application of large mean tensile stresses during fatigue loading results in a decrease in the cross-sectional area of the specimen and a concomitant increase in the true stress. A more accurate definition would be "mean load."

In the sections below, data for the various materials are described separately for the sake of clarity. The results for the zero mean stress tests were taken from references 1 through 3.

3.1 Type 304 Stainless Steel Data

The mean stress fatigue data in Table 2 are plotted in Figures 3 and 4. For room temperature tests, a mean tensile stress, σ_m , of about 6.5 ksi increases the fatigue strength in the lower-cycle region but will give rise to a decrease in the endurance limit. In the case of the 1100°F tests, mean stresses in the range 6-8 ksi are again beneficial but, for significantly higher values where creep is expected, the fatigue strength is greatly reduced. For the limiting case in Figure 4, where the alternating stress, σ_a , is zero, failure times were obtained from the stress-rupture tests given in Table 3. It is obvious that as the alternating stress decreases, and the mean tensile stress increases, there is a tendency to

tests, for which the range of applied stress is zero. Although it seems that the Goodman diagram is adequate for conservatively estimating mean stress effects in the low- σ_m region, caution must be exercised since the tests were of limited duration. For the test times used in this study the beneficial effects of low- σ_m values may be explained in terms of the amounts of plasticity occurring during fatigue - Figure 7. For fully-reversible deformation there is usually a finite plastic strain component, $\Delta\epsilon_p$. For low mean stress conditions, however, the deformation is predominantly elastic, which results in smaller rates of damage accumulation and, therefore, enhanced fatigue life. At higher mean stresses the beneficial effects disappear, probably because of the increased creep damage rate and the greater reduction in specimen cross-sectional area, which arises from the large value of the permanent tensile strain $\Delta\epsilon'$ (Figure 7).

Summarized below are the various analytical expressions which have been found inadequate in predicting long-term mean stress fatigue effects:

$$\sigma_a = \sigma_0 [1 - (\sigma_m/\sigma_u)] \quad \text{Goodman Law} \quad (1)$$

$$\sigma_a = \sigma_0 [1 - (\sigma_m/\sigma_u)^2] \quad \text{Gerber Law} \quad (2)$$

$$\sigma_a = \sigma_0 [1 - (\sigma_m/\sigma_y)] \quad \text{Soderberg Law} \quad (3)$$

in which:

σ_0 = fatigue limit for fully-reversible fatigue

σ_u = ultimate tensile strength

σ_y = yield strength

The limitations in their usefulness stem from the fact that time-independent functions, such as yield and tensile strengths, cannot be used to correlate fatigue processes which include a time-dependent creep component. It was, therefore, decided to investigate a different approach based on times-to-failure, t_f , rather than the fail/no-fail criteria used in Eqs. (1) through (3). The data in Figure 4 were re-plotted in the form of "isochronous mean stress fatigue curves" (Figure 8). These were obtained by drawing "vertical" lines through the 10 , 10^2 , 10^3 h etc. points in Figure 4, and determining the combinations of σ_a and σ_m which give failure in a given time. All of the points along the mean stress axis in Figure 8 were obtained from the stress-rupture data given in Table 3. It was found that, to a good approximation, the mean and alternating stresses for a given t_f were related by a simple cubic expression, as shown in Figure 9, viz.:

$$\sigma_a = \sigma_0 - B\sigma_m^3 \quad (4)$$

B is a material constant and σ_0 is the fatigue strength for the zero mean stress condition. For the t_f range evaluated, σ_0 is a constant, equal to 21.5 ksi. The significance of B may be deduced from the relationships in Figure 9. For a given time-to-failure, t_f ,

$$\sigma_a = \left[\sigma_0 - B\sigma_m^3 \right] t_f \quad (4b)$$

For the boundary condition $\sigma_a = 0$, the mean stress will be equal to the creep-rupture stress value, σ_r . Hence, from Eq. (4b):

$$0 = \sigma_0 - B\sigma_r^3 \quad (4c)$$

or

$$B = \sigma_0 / \sigma_r^3 \quad (4d)$$

From Eqs. (4) and (4d):

$$\sigma_a = \sigma_0 \left[1 - \left(\frac{\sigma_m}{\sigma_r} \right)^3 \right]_{t_f} \quad (4e)$$

This expression takes time-dependent deformation into consideration through the rupture strength term σ_r . A knowledge of the fatigue limit, σ_0 , for fully-reversible deformation, and the rupture strength for a given t_f will, therefore, allow the isochronous mean stress fatigue curve to be calculated.

To check this equation, values of the rupture strength for 10, 10^2 , 10^3 h, etc., were taken from the data in Table 3, and calculated isochronous curves were obtained. A comparison with experimental curves is given in Figure 10, and good agreement is shown.

Equation (4e) may be rewritten in the form:

$$\left(\frac{\sigma_a}{\sigma_0} \right) + \left(\frac{\sigma_m}{\sigma_r} \right)^3 = 1 \quad (4f)$$

In this form the damage components due to fatigue and creep are separated and shown to total up to unity for a given t_f value. Equation (4f) represents a special case of the creep-fatigue interaction since it is applicable to cases where creep and fatigue damage is allowed to occur simultaneously. In much of the work described in the open literature the test conditions are adjusted so that creep and fatigue increments are

applied alternately.

For cyclic frequencies other than the 40 Hz used in this work, a different set of isochronous curves would be obtained because of the change in the relationship between t_f and N_f .

Also shown in Figure 8 are the various regions where failure is controlled by creep, fatigue, and a combination of creep and fatigue. These were defined from the metallographic study described in Section 5.

3.2 Normalized and Tempered 2½Cr-1Mo Steel Data

The data in Table 4 and Figure 11 show the effects of mean stress on the fatigue of normalized and tempered 2½Cr-1Mo steel. Although the information is not as comprehensive as that for Type 304 stainless steel, it may be seen that tensile mean stresses generally reduce the fatigue strength, especially in the range of 20 ksi, and greater. From the Goodman diagram (Figure 12) the creep data points lying along the mean stress line and some of the mean stress stress fatigue points lie close to, or within, the "safe" region. Hence, the Goodman procedure is not conservative in estimating long-term, mean stress conditions.

Following the procedure used for Type 304 stainless steel, isochronous mean stress curves may be obtained (Figure 13). The creep and fatigue failure regimes closely follow those described for Type 304 stainless steel - see Section 5.

A cubic relationship, similar to that for Type 304 stainless steel (Eq. 4e), was also found to be valid for 2½Cr-1Mo steel. However, in this case, σ_0 was found to be dependent on t_f , as shown in Figure 14. From Figure 15 it may be shown that:

$$\log \sigma_0 = 1.602 - 0.0157 \log t_f \quad (5)$$

A comparison between calculated and experimental isochronous mean stress fatigue curves may be made using Eqs. (4e) and (5), and the results are given in Figure 16. The agreement is good except for the 10 h curve for which the calculated value is overly conservative.

3.3 Incoloy-800H Data

Table 5 and Figures 17 through 19 show mean stress effects for Incoloy-800H at 1100°F. The Goodman diagram shows that even at low mean stresses of 10 ksi, the procedure does not give conservative results.

An attempt was made to fit the Incoloy-800H data to an expression of the type shown in Eq. (4e). Poor results were obtained and a more sophisticated computer analysis was found necessary. This involved a regression analysis to fit the data in Figure 19 to an equation of the form:

$$\sigma_a = \sigma'_0 - B (\sigma_m + C)^3 \quad (6)$$

in which σ'_0 , B and C are material constants. Note that σ'_0 is not the fatigue limit for fully-reversible deformation since σ_a is not equal to σ'_0 , when σ_m is reduced to zero.

Consider the case when σ_a is zero. From Eq. (6):

$$B = \sigma'_0 / (\sigma_r + C)^3 \quad (6b)$$

Hence, from Eqs. (6) and (6b):

$$\sigma_a = \sigma'_0 \left[1 - \left(\frac{\sigma_m + C}{\sigma_r + C} \right)^3 \right] \quad (6c)$$

When σ_m is zero in Eq. (6c):

$$\sigma_a = \sigma_0 = \sigma'_0 \left[1 - \left(\frac{C}{\sigma_r + C} \right)^3 \right] \quad (6d)$$

From Eqs. (6c) and (6d), therefore:

$$\sigma_a = \sigma_0 \left[1 - \left(\frac{C}{\sigma_r + C} \right)^3 \right]^{-1} \left[1 - \left(\frac{\sigma_m + C}{\sigma_r + C} \right)^3 \right]_{t_f} \quad (6e)$$

A knowledge of the fatigue limit for fully-reversible deformation, σ_r , σ_f , and C will permit the isochronous mean stress fatigue curves to be calculated. Values of C , obtained from the regression analyses, are given in Figure 20.

Note that Eq. (4e), which applies to Type 304 stainless steel and 2½Cr-1Mo steel, is a special case of Eq. (6e) for the condition $C = 0$.

A comparison of calculated and experimental isochronous mean stress fatigue curves for Incoloy-800H is given in Figure 21 and the agreement is seen to be good.

Limited information was obtained for a low-carbon heat of Incoloy-800 (Heat HH7531A) - see Table 5 and Figure 22. The effects of mean tensile stresses are very detrimental as is the case for Incoloy-800H described previously. Using data on fully-reversible deformation from reference 1, a Goodman diagram was constructed (Figure 23). The ultimate tensile strength value was estimated from a study conducted on an alloy of very similar chemical composition.⁷ As for the other materials described above, the Goodman diagram does not give a conservative estimate of mean

stress effects.

4. Strain Accumulation During Test

During fully-reversible fatigue, changes in specimen length are not usually expected unless there is a substantial difference between tensile and compressive flow, such as for the Bauschinger effect.⁶

In Table 6 are summarized the results of measurements made on a variety of samples tested at BNL for the fully-reversible condition. Based on changes in specimen length and diameter, 2½Cr-1½O steel and Type 304 stainless steel do not appear to show any strain accumulation. In the case of Incoloy-800, however, there is an indication that strain accumulation does occur for fully-reversible fatigue. At this time the reasons for this are obscure, and further work is needed to determine whether the strain continuously increases with time, or whether it is associated with the initial stages of deformation prior to the establishment of more stable hysteresis loop conditions.

For applied mean stress situations a net increase in specimen length would be expected at high temperatures, where creep and fatigue occur simultaneously. The data in Figures 24 through 27 show that the amount of strain accumulation is dependent on the ratio σ_a/σ_m . In the case of failed specimens, actual strain measurements based on the reduction in cross sectional area usually could not be made because of severe deformation near the fracture zone. It was, therefore, decided to use the overall specimen length as a measure of strain. From these data it is clear that for Type 304 stainless steel and Incoloy-800H the strain accumulation at

failure increases as σ_a/σ_m is increased from zero. At some particular value of σ_a/σ_m , however, a transition is reached after which increasing σ_a/σ_m ratios give rise to smaller amounts of strain.

It should be noted that all of the strain measurements made in this work are not uniquely dependent on the σ_a/σ_m ratio, since a given value of σ_a/σ_m may be obtained from infinite combinations of σ_a and σ_m . Hence, a test run for a combination of $\sigma_a = 10/\sigma_m = 20$ ksi would not necessarily give the same strain accumulation as that for $\sigma_a = 20/\sigma_m = 40$ ksi. In general, however, it would be anticipated that stress ratios close to zero would encourage creep-type failure, whereas high σ_a/σ_m values would promote fatigue failure - see Section 5.

For the unfailed samples in Tables 3 and 5 accurate estimates of strain accumulation may be made based on the reductions in cross sectional area. Such measurements would not be complicated by severe distortion around a fracture zone or by the presence of wide fatigue/creep cracks which are frequently observed after failure. The data in Table 7 show that significant strain accumulation occurs for both Type 304 stainless steel and Incoloy-800. Although the data are limited it is probable that strain accumulation is encouraged by:

- Increasing temperature
- Accumulated fatigue cycles
- Increasing mean stress
- Increasing alternating stress

An interesting observation in Figures 24 through 27 is that for the high σ_a/σ_m range, where creep is controlling failure, the slopes of the

curves for Type 304 stainless steel and Incoloy-800H are negative, whereas for 2½Cr-1Mo and low-carbon Incoloy-800 they are positive. This could be connected with the observation that the first two materials are cyclically hardened,⁸ whereas normalized and tempered 2½Cr-1Mo,⁹ and possibly also low-carbon Incoloy-800, are cyclically softened. Since a cyclically work-hardened material would be continuously strengthened with time, the amount of creep-induced strain, under a given mean stress, would be greater for the lower cyclic stress values. Conversely, creep under a given mean stress for a cyclically-softened steel, would be enhanced for large σ_a values since the rate of softening should be greater.

The detrimental effects of mean stress on fatigue life may be considered from a different standpoint - that of stress-rupture life. In Figure 28 are plotted rupture times for specimens which are subjected to various combinations of σ_a and σ_m , including the case for pure stress-rupture where σ_a is zero. Extremely large reductions in rupture time are noted for cyclically-stressed specimens, even though the maximum stress is frequently very much less than the steady state stress level for the standard stress-rupture tests. For the Type 304 stainless steel tests it is seen that even small cyclic stresses of 8-10 ksi decrease the rupture time by a factor of about 3 at 1100°F. There is, obviously, a need for more definitive data on the effects of small high-frequency cyclic stresses on the creep and stress-rupture behavior of reactor materials.

5. Metallographic Evaluation of Failure Mechanisms

Comprehensive optical and scanning electron microscope (SEM) observations have been made on fractured samples to delineate the roles of creep and fatigue in the failure process. This will enable an estimate to be made of the likely failure mode for any specified combination of σ_a and σ_m . In Figures 29 through 31 are given SEM fractographs of most of the materials tested. For Type 304 stainless steel the fracture surfaces are very similar for specimens tested under conditions where $\sigma_a/\sigma_m = 0$ (stress-rupture) and $\sigma_a/\sigma_m = 0.32$. A dimpled type of surface is seen which is indicative of ductile creep fracture. When σ_a/σ_m is increased to 0.72, however, fatigue begins to influence the fracture process, as seen by the appearance of a small fatigue step in the lower right-hand side of the fracture surface. This crack does not propagate very far and most of the remaining surface suffers a creep-type failure. For $\sigma_a/\sigma_m = 2.70$, the failure mode is pure fatigue. The crack propagates through most of the gauge diameter and, in the final stages of fracture, a chisel-edge failure zone is formed.

The optical micrographs in Figures 32(a) and 32(b) are longitudinal sections through Type 304 stainless steel SEM samples described in Figure 29. The sectioning was such that the plane of observation for the fatigue-failed specimens intersected the point of crack initiation and the area of final separation. In micrographs b2 through d2 the fracture path is that formed by the propagating fatigue crack. Micrographs b1 through d1 show the areas where final separation occurred. All of the optical micrographs in this work are oriented such that the stress axis is close to the vertical direction in the plane of the page.

For the stress-rupture specimen, the amount of grain-boundary sliding and crack formation is not very pronounced. Some grain-boundary cavities are formed in the creep process but they are relatively large and few in number. The particular specimen shown in Figure 32(a) (MSI-107) was loaded at 36 ksi and failed quickly after 48.8 hours. This resulted in a smaller amount of grain-boundary cracking than would be expected for a longer duration test. As the σ_a/σ_m ratio increases, the proportion of creep to fatigue damage decreases. This is clear from the decrease in the amounts of grain-boundary cracking and grain elongation. In addition, as the stress ratio increases, the failure changes from an intergranular to a transgranular mode. Based on the SEM and optical microscopy studies, approximate boundaries are drawn in Figure 8 to delineate between creep, fatigue and creep/fatigue failure zones.

The SEM fractographs for Incoloy-800H in Figure 30 show that in the stress-rupture specimen the failure is predominantly intergranular. When the stress ratio is increased to values of 1.25 and 2.70, fatigue failures occur. The main difference in the two cases is that for the higher stress ratio, there is a greater reduction in area at fracture, and the fracture surface is smoother and more uniform in shape.

The optical micrographs in Figures 33(a) and 33(b) confirm that for the mean stress fatigue tests shown in Figure 32, the failure mode is fatigue with crack propagation proceeding intergranularly. For the specimens tested at $\sigma_a/\sigma_m = 1.25$, however, there is a small amount of creep damage in the form of grain-boundary cavities. These become more pronounced and elongated in the area of final separation. Figure 19 shows estimated

areas where creep, fatigue, and creep/fatigue type failures may be anticipated.

For the 2½Cr-1Mo steel the SEM fractographs in Figure 31 show that in typical stress-rupture tests a cup-and-cone type failure is likely. Two specimens tested for σ_a/σ_m ratios of 1.60 and 4.00 showed fatigue cracks propagating across approximately half of the gauge diameter, with final separation occurring by very pronounced necking to a fine point.

The optical micrographs in Figures 34(a) and 34(b) show that very severe grain elongation is present in the stress-rupture sample but very little is seen in the two mean stress fatigue samples examined, except in the region where final failure occurred. The samples clearly failed by fatigue, with only minute amounts of grain-boundary cavitation which occurred in the areas where final separation took place. Figure 13 shows the estimated boundary between creep- and fatigue-controlled failures. The metallographic studies did not clearly reveal the presence of a creep/fatigue failure zone. If one exists it occurs for mean stress values in excess of 20 ksi. No tests, however, were run in this regime.

An interesting observation in Figures 34(a) and 34(b) is that for the specimen showing a σ_a/σ_m ratio of 1.60 the fatigue crack surface is indented with uniformly oriented crevices, or striations. In these tests the direction of crack propagation is from left to right. For a stress ratio of 4.00 the specimen showed a much more uniform surface, although one large indentation seems to be present. It is possible that the difference in the smoothness of the fatigue crack surface is related to the transition from intergranular to transgranular failure, but this seems un-

likely based on the regular orientation of the striations. Most likely, the striations represent locations where the propagating fatigue crack is temporarily at rest, as suggested by Laird.¹⁰ If a single striation is formed by each fatigue cycle the average rate of crack propagation may be estimated. Assume that the crack propagation distance is about half the width of the specimen diameter, as suggested by Figure 31. This is equal to 0.06 inch. From Figure 34(a) there are about 1200 striations per inch; hence, the number of striations in 0.06 inch is about 72. For the cycling rate used, 40 Hz, the fatigue crack would propagate in about 2 seconds, which is an extremely fast rate. Compared to low-cycle fatigue, therefore, the consequences of fatigue failure are far more severe under high-cycle conditions since failure would be too fast for preventative action to be taken once the crack had reached a critical size.

In Section 4 it was stated that the differences in the amounts of strain accumulation between Type 304 stainless steel and Incoloy-800H on the one hand, and 2½Cr-1Mo on the other, lay in the nature of the cyclic work hardening processes. The SEM fractographs show that for the austenitic materials the degree of elongation in the areas where final separation occurs are far smaller than those for the 2½Cr-1Mo steel, which tend to neck to a fine point. The metallographic observations are consistent with the proposed model since materials which become cyclically softened would tend to show increased elongation as σ_a/σ_m increases, whereas for cyclically-hardened materials the reverse would be true.

Examination of failed low-carbon Incoloy-800 samples showed fracture

surfaces similar to those for $2\frac{1}{2}\text{Cr-1Mo}$ steel, indicating that this, too, is a cyclically-softened alloy. The positive gradients of the strain accumulation lines in Figure 27 are also consistent with those for the ferritic material.

6. Discussion and Conclusions

High-cycle fatigue conditions exist in many reactor structures and are induced by mechanical, thermal or acoustic excitation. To date, most of the limited data available are for fully-reversible loading which does not cover situations where a mean stress is present. This stress state is an extremely important one since it occurs frequently in a reactor system, and it can lead to significant creep and strain accumulation. The work conducted in this study shows that when the mean stress is sufficiently high, drastic reductions in high-cycle fatigue life result. Conversely, it may be stated that cyclic stresses greatly reduce the creep-rupture strength of a material. Below are listed some of the conclusions formulated in this work, which was performed to quantify the synergistic effects of fatigue and creep for high-cycle loading conditions:

- High-cycle fatigue under a mean-stress condition represents a special case of the creep-fatigue interaction, but differs in the sense that creep and fatigue occur simultaneously, rather than alternately, as is the common situation for low-cycle studies.
- For sufficiently large mean stresses, Type 304 stainless steel, low-carbon Incoloy-800, Incoloy-800H, and normalized and tempered $2\frac{1}{2}\text{Cr-1Mo}$ steel show a large decrease in creep strength.

- The effects of the mean stress cannot be evaluated at high temperatures and high mean stresses using the Goodman, Gerber, and Soderberg approaches since these correlations are based on time-independent deformation which exists at low temperature where creep is absent.
- A correlation based on time-dependent deformation has been developed which relates the alternating and mean stresses to the time to failure. In its basic form it states:

$$\sigma_a = \sigma_0 [1 - (\sigma_m/\sigma_r)^3] t_f$$

The value of σ_0 , the fatigue strength for fully-reversible deformation, may be a function of the failure time, t_f .

- Strain accumulation usually occurs when a mean stress is applied during fatigue. A possible exception to this is for Incoloy-800H which shows a clear indication of tensile strain accumulation under fully-reversible loading.
- The amount of strain accumulation depends on the ratio of σ_a to σ_m and on the work hardening (or softening) characteristics of the material.
- Low σ_a/σ_m values lead to creep-controlled failure, whereas high values encourage fatigue failure. For the creep-type failures intergranular crack propagation is encountered, whereas for fatigue failure the cracking is transgranular.
- Under certain conditions, 2½Cr-1Mo steel exhibits striated fatigue fracture surfaces, which may be used to estimate crack propagation

rates. Based on these metallographic observations it seems that a fatigue crack of critical size can propagate through a specimen in just a few seconds. This represents a more significant problem compared to low-cycle deformation where crack propagation rates may be sufficiently slow to permit corrective action to be taken.

Acknowledgements

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Table 1

Chemistries of High-Cycle Fatigue Test Materials

Material ⁽¹⁾	Heat	Concentration (Wt. %)											
		C	P	Ni	Mn	Cr	Si	Mo	S	Cu	Ti	Al	Fe
T304 SS	55697	0.06	0.016	9.38	0.91	18.50	0.50	0.05	0.037	0.10	-	-	Bal.
T304 SS	BNL Heat	0.08	0.039	9.55	1.74	18.68	0.63	0.25	0.015	0.27	-	-	Bal.
I-800H	HH 3113A	0.06	-	32.11	0.90	20.35	0.38	-	0.007	0.25	0.39	0.36	45.2
I-800H	HH 7427A	0.05	-	32.17	0.67	19.83	0.46	-	0.003	0.65	0.43	0.39	45.4
I-800	HH 7531A	0.03	-	32.44	1.05	19.25	0.26	-	0.007	0.16	0.20	0.10	46.5
2½Cr-1Mo	Exptl.	0.12	0.010	0.21	0.44	2.20	0.40	0.91	0.015	-	-	-	Bal.

NOTE: (1) Type 304 stainless steels solution-annealed at 1950°F followed by water quench.

All Incolloys solution-annealed at 2100°F followed by water quench.

2½Cr-1Mo steel normalized from 1700°F and tempered at 1300°F.

Table 2

High-Cycle Mean-Stress Fatigue Data for Solution-Treated Type 304 Stainless Steel

Spec. No.	Test Temp. (°F)	Stress (ksi)		Cycles to Failure (N_f) ⁽¹⁾	Final Spec. Length (in) ⁽²⁾	Final Spec. Diam. (in)	Orig. Spec. Diam. (in)
		Mean	Cyclic				
MS1-83	72	5.5	27.5	$>7.2 \times 10^7$	2.630	0.1240	0.1251
MS1-82	72	6.0	30.0	2.7×10^5	2.674		
MS1-87	72	6.0	30.0	$>6.6 \times 10^6$	2.633	0.1245	0.1249
MS1-86	72	6.25	31.2	1.3×10^5	2.675		
MS1-85	72	6.75	32.7	6.1×10^4	2.671		
MS1-74	72	7.5	37.5	2.3×10^4	2.695		
MS1-98	1100	6.0	22.0	$>1.0 \times 10^8$	2.664	0.1175	0.1250
MS1-89	1100	6.0	22.0	$>7.2 \times 10^7$	2.636	0.1235	0.1251
MS1-96	1100	6.0	22.8	9.3×10^4	2.683		
MS1-97	1100	6.0	22.8	9.3×10^4	2.690		
MS1-95	1100	6.0	24.0	6.8×10^4	2.679		
MS1-94	1100	6.0	26.0	2.0×10^4	2.680		
MS1-93	1100	8.0	20.0	$>1.0 \times 10^8$	2.660	0.1190	0.1251
MS1-92	1100	8.0	21.6	4.0×10^5	2.695		
MS1-90	1100	8.0	22.0	3.8×10^5	2.690		
MS1-91	1100	8.0	22.8	7.9×10^5	2.685		
MS1-88	1100	8.0	24.0	4.8×10^4	2.695		
MS1-111	1100	12.0	18.0	$>1.2 \times 10^8$	2.638	0.1235	0.1260
MS1-113	1100	16.0	14.0	$>1.2 \times 10^8$			
MS1-112	1100	16.0	16.0	2.4×10^7	2.730		
MS1-137	1100	16.0	19.0	1.2×10^7	2.703		

Table 2 - Cont'd.

Spec. No.	Test Temp. (°F)	Stress (ksi)		Cycles to Failure (N_f) ⁽¹⁾	Final Spec. Length (in) ⁽²⁾	Final Spec. Diam. (in)	Orig. Spec. Diam. (in)
		Mean	Cyclic				
MS1-129	1100	20.0	10.0	$>1.7 \times 10^7$	2.650	0.1170	0.1245
MS1-132	1100	25.0	8.0	4.4×10^7	2.690		
MS1-131	1100	25.0	10.0	1.9×10^7	2.695		
MS1-133	1100	25.0	12.0	4.2×10^7	2.690		
MS1-136	1100	25.0	18.0	1.1×10^6	2.715		

Notes: (1) Cyclic frequency is 40 Hz.

(2) The original specimen length is 2.625

Table 1

Stress-Rupture Data for Type 304 Stainless Steel, Incoloy-800H
and Normalized and Tempered 2½Cr-1Mo Steel

<u>Material</u>	<u>Specimen No. (1)</u>	<u>Temp. (°F)</u>	<u>Stress (ksi)</u>	<u>Rupture Time (h)</u>	<u>Spec. Length at Fracture (in)</u>
T304 SS	MS1-103	1100	45.0	6.5	
	MS1-105	1100	38.0	21.5	
	MS1-107	1100	36.0	48.8	2.696
	MS1-106	1100	30.0	238.0	2.689
	MS1-108	1100	27.0	337.5	2.691
I-800H	UN1-52	1100	49.0	32.3	
	UN1-39	1100	48.0	43.3	
	UN1-38	1100	45.0	156.0	
	UN1-55	1100	45.0	199.5	
	UN1-40	1100	43.0	95.8	
	UN1-41	1100	43.0	170.0	
	UN1-42	1100	40.0	238.3	
N&T 2½Cr-1Mo	UC1-50	1000	37.0	36.5	
	UC1-51	1000	34.0	62.0	
	UC1-52	1000	32.0	182.0	

NOTE: (1) M specimens are hourglass type and U specimens are straight-sided. Type 304 stainless steel specimens from Heat 55697; Incoloy-800H specimens are from Heat MH 3113A.

Table 4

High-Cycle Mean-Stress Fatigue Data for Normalized
and Tempered 2½Cr-1Mo Steel

<u>Spec. No.</u>	<u>Test Temp. (°F)</u>	<u>Stress (ksi)</u>		<u>Cycles to Failure (N_f)⁽¹⁾</u>	<u>Final Spec.⁽²⁾ Length (in)</u>
		<u>Mean</u>	<u>Cyclic</u>		
MC1-48	1000	10.0	34.0	1.1×10^7	2.672
MC1-33	1000	10.0	38.0	2.5×10^6	-
MC1-34	1000	10.0	40.0	5.7×10^6	2.666
MC1-35	1000	10.0	42.0	3.4×10^7	2.660
MC1-43	1000	10.0	42.5	1.3×10^5	2.673
MC1-42	1000	10.0	46.0	1.2×10^4	2.688
MC1-41	1000	10.0	50.0	4.0×10^3	2.705
MC1-47	1000	20.0	30.0	1.5×10^7	2.671
MC1-45	1000	20.0	32.0	1.0×10^7	2.673
MC1-46	1000	20.0	36.0	2.6×10^6	2.671

Notes: (1) Cyclic frequency is 40 Hz.

(2) The original specimen length is 2.625 ± 0.005 in.

Table 5

High-Cycle Mean-Stress Fatigue Data for Incoloy-800 and Incoloy-800H

Spec. No.	Test Temp. (°F)	Stress (ksi) Mean	Cyclic	Cycles to Failure (N_f)(1)	Final Spec. Length (in)(2)	Final Spec. Diam. (in)	Orig. Spec. Diam. (in)
<u>Heat HH 3113A (0.06% C)</u>							
MN1-23	1100	10.0	26.0	6.4×10^6	2.749		
MN1-22	1100	10.0	27.0	1.2×10^6	2.710		
MN1-19	1100	10.0	30.0	9.0×10^5	2.705		
MN1-21	1100	10.0	32.0	1.4×10^5			
MN1-17	1100	20.0	25.0	4.2×10^6	2.719		
MN1-20	1100	20.0	28.0	3.8×10^6	2.725		
<u>Heat HH 7427A (0.05% C) (3)</u>							
MNF-137	1100	10.0	22.0	$>1.2 \times 10^8$	3.978	0.2475	0.2510
MNF-133	1100	20.0	20.0	$>1.2 \times 10^8$	3.945	0.2385	0.2530
<u>Heat HH 7531A (0.03% C)</u>							
MN1-84	1100	10.0	26.0	1.1×10^5	2.695		
MN1-94	1100	10.0	29.0	2.0×10^4	2.710		
MN1-82	1100	20.0	20.0	6.5×10^6	2.694		
MN1-81	1100	20.0	25.0	3.1×10^5	2.721		
MN1-71	1200	10.0	18.0	$>1.0 \times 10^8$	2.630	0.1255	0.1255
MN1-70	1200	10.0	20.0	6.5×10^5	2.699		
MN1-80	1200	10.0	23.0	5.6×10^4	2.708		
MN1-72	1200	15.0	16.0	$>1.1 \times 10^8$	2.630	0.1225	0.1255
MN1-73	1200	15.0	18.0	7.0×10^6	2.695		
MN1-78	1200	15.0	20.0	$>9.4 \times 10^5$	2.647	0.1200	0.1255
MN1-77	1200	15.0	22.0	1.1×10^6	2.712		

NOTES: (1) The cyclic frequency is 40 Hz.

(2) The original specimen length is 2.625 inches except for Heat HH7427A where it is 3.938 inches.

(3) 1/4-inch diameter specimens.

Table 6

Dimensional Changes in Structural Materials During High-Cycle,
Load-Controlled, Fully-Reversible Fatigue Testing

<u>Spec. No.</u>	<u>Heat Number</u>	<u>Test Temp. (°F)</u>	<u>Cyclic Stress (ksi)</u>	<u>Accum. Cycles⁽¹⁾</u>	<u>Final Spec. Length (in)</u>	<u>Orig. Spec. Length (in)⁽²⁾</u>	<u>Final Spec. Diam. (in)</u>	<u>Orig. Spec. Diam. (in)</u>
<u>2½Cr-1Mo Steel (0.120% C, N & T)</u>								
MC1-24	-	1000	30.0	5.3×10^7	2.626	2.625	0.124	0.126
<u>Solution-Annealed Type 304 Stainless Steel</u>								
MS1-109	55697	72	17.5	1.1×10^7	2.631	2.625	0.125	0.125
MS1-60	55697	800	20.6	1.5×10^8	2.622	2.625	0.127	0.126
MS1-42	55697	1100	20.4	1.7×10^8	2.631	2.625	0.125	N/M ⁽³⁾
WB-3 ⁽⁴⁾	BNL Ht.	1100	24.0	6.2×10^7	2.625	2.625	0.125	N/M
WB-5 ⁽⁵⁾	BNL Ht.	1100	24.0	1.4×10^8	2.603		0.125	N/M
<u>Incoloy-800 and Incoloy-800H</u>								
MN1-127	HH5556A	1000	33.0	2.0×10^7	2.625	2.625	0.125	0.126
MN1-130	HH5556A	1000	34.5	1.7×10^7	2.623	2.625	0.124	0.126
MN1-50	HH7531A	1100	20.0	1.3×10^8	2.640	2.625	0.120	N/M
MN1-53	HH7531A	1100	20.0	1.8×10^7	2.636	2.625	0.124	N/M
MN1-41	HH3113A	1200	25.0	1.9×10^7	2.635	2.625	0.124	0.125
MN1-42	HH3113A	1200	26.0	7.8×10^7	2.625	2.625	0.123	0.125
MN1-65	HH7531A	1200	26.4	1.4×10^8	2.627	2.625	0.126	0.126

- Notes:
- (1) Cyclic frequency is 40 Hz except for specimen MS1-109 which was cycled at 5 Hz.
 - (2) Nominal value for all machined samples.
 - (3) Values not measured.
 - (4) Thermally aged 1000°F/2100 h prior to testing.
 - (5) Thermally aged 1000°F/5000 h prior to testing.

Table 7

Tensile Strain Accumulation in Unfailed, High-Cycle

Mean-Stress Fatigue Samples

Spec. No.	Test Temp. (°F)	Stress (ksi)		Accumulated Cycles	Tensile Strain (%)(1)
		Mean	Cyclic		
<u>Type 304 Stainless Steel</u>					
MS1-83	72	5.5	27.5	7.2×10^7	1.78
MS1-87	72	6.0	30.0	6.6×10^6	0.64
MS1-98	1100	6.0	22.0	1.0×10^6	13.17
MS1-89	1100	6.0	22.0	7.2×10^7	2.61
MS1-93	1100	8.0	20.0	1.0×10^8	10.51
MS1-111	1100	12.0	18.0	1.2×10^8	4.09
MS1-129	1100	20.0	10.0	1.7×10^7	13.23
<u>Incoloy-800 (0.03% C, Heat HH 7531A)</u>					
MN1-71	1200	10.0	18.0	1.0×10^8	0
MN1-72	1200	15.0	16.0	1.1×10^8	4.96
MN1-78	1200	15.0	20.0	9.4×10^5	9.38
<u>Incoloy-800H (0.05% C, Heat HH 7427A)</u>					
MNF-137	1100	10.0	22.0	1.2×10^8	2.84
MNF-133	1100	10.0	20.0	1.2×10^8	12.53

NOTE: (1) Based on diametral measurements and a constancy-of-volume criterion.

Figure 1. Microstructures of high-cycle fatigue test materials:

- (a) Type 304 stainless steel (heat 55697), 200X;
- (b) Type 304 stainless steel (BNL heat), 200X;
- (c) Incoloy-800H (heat HH 3113A), 200X;
- (d) Incoloy-800H (heat HH 7427A), 200X;
- (e) Incoloy-800 (heat HH 7531A), 200X;
- (f) Normalized and tempered $2\frac{1}{2}\text{Cr}-1\text{Mo}$ steel (exptl. heat), 320X.

MTS FATIGUE SPECIMEN

ULTRASONIC FATIGUE SPECIMEN

Figure 2. Specimen configurations for fatigue and stress-rupture testing.

Figure 3. Effect of a mean tensile stress on the high-cycle fatigue of solution-treated Type 304 stainless steel at 72°F.

Figure 4. Effect of a mean tensile stress on the fatigue of solution-treated Type 304 stainless steel at 1100°F.

Figure 5. Goodman diagram for solution-treated Type 304 stainless steel at 72°F.

Figure 6. Goodman diagram for solution-treated Type 304 stainless steel at 1100°F.

Figure 7. Effect of mean stress on the fatigue hysteresis loop.

Figure 8. Isochronous mean stress fatigue curves for solution-treated Type 304 stainless steel at 1100°F.

Figure 10. Comparison of calculated and experimental isochronous mean-stress high-cycle fatigue curves for solution-treated Type 304 stainless steel at 1100°F.

Figure 9. Relationship between the alternating and mean stresses for the high-cycle fatigue of Type 304 stainless steel at 1100°F.

Figure 11. Effect of a mean tensile stress on the high-cycle fatigue of normalized and tempered 2½Cr-1Mo steel at 1000°F.

Figure 12. Goodman diagram for normalized and tempered 2½Cr-1Mo steel at 1000°F.

Figure 13. Isochronous mean stress fatigue curves for normalized and tempered 2½Cr-1Mo steel at 1000°F.

Figure 14. Relationship between the alternating and mean stresses for the high-cycle fatigue of normalized and tempered 2½Cr-1Mo steel at 1000°F.

Figure 15. Values of σ_0 for normalized and tempered $2\frac{1}{2}\text{Cr}-1\text{Mo}$ steel mean-stress high-cycle fatigue data at 1000°F .

Figure 17. Effect of a mean tensile stress on the high-cycle fatigue of Incoloy-800H at 1100°F .

Figure 16. Comparison of calculated and experimental isochronous mean-stress high-cycle fatigue curves for normalized and tempered $2\frac{1}{2}\text{Cr}-1\text{Mo}$ steel at 1000°F .

Figure 18. Goodman diagram for Incoloy-800H at 1100°F.

Figure 19. Isochronous mean stress fatigue curves for Incoloy-800H at 1100°F.

Figure 20. Values of C for Incoloy-800H mean-stress high-cycle fatigue data at 1100°F.

Figure 21. Comparison of calculated and experimental mean-stress high-cycle fatigue curves for Incoloy-800H at 1100°F.

Figure 22. Effects of mean stress on the high cycle fatigue of solution treated low carbon Incoloy-800 at 1200°F.

Figure 23. Goodman diagram for low carbon Incoloy-800 at 1200°F.

Figure 24. Strain accumulation in solution-treated Type 304 stainless steel under mean-stress high-cycle fatigue conditions.

Figure 25. Strain accumulation in normalized and tempered 2½Cr-1Mo steel at 1000°F under mean-stress high-cycle fatigue conditions.

Figure 26. Strain accumulation in Incoloy-800H under mean-stress high-cycle fatigue conditions at 1100°F.

Figure 27. Strain accumulation in low carbon Incoloy-800 under mean stress high cycle fatigue conditions.

Figure 28. Effect of fatigue cycling on stress rupture life.

Figure 29. Fractography of solution-treated Type 304 stainless steel mean-stress high-cycle fatigue specimens at 1100°F; (a) stress-rupture specimen loaded at 36.0 ksi, (b) $\sigma_a/\sigma_m \approx 0.32$, (c) $\sigma_a/\sigma_m = 0.72$, (d) $\sigma_a/\sigma_m = 2.70$; magnifications 36X.

Figure 30. Fractography of Incoloy-800H at 1100°F;
 (a) stress-rupture specimen loaded at
 49.0 ksi, (b) $\sigma_a/\sigma_m = 1.25$, (c) σ_a/σ_m
 $= 2.70$; magnifications 36X.

Figure 31. Fractography of normalized and tempered $2\frac{1}{2}\text{Cr}-1\text{Mo}$ steel at 1000°F ; (a) stress-rupture specimen loaded at 34.0 ksi, magnification 80X, (b) $\sigma_a/\sigma_m = 1.60$, magnification 36X, (c) $\sigma_a/\sigma_m = 4.00$, magnification 36X.

Figure 32(a). Morphology of fracture in solution treated Type 304 stainless steel mean-stress high-cycle fatigue specimens at 1100°F; (a) stress-rupture specimen loaded at 36.0 ksi, (b1, b2) $\sigma_a/\sigma_m = 0.32$. Magnifications 100X.

Figure 32(b). Morphology of fracture in solution treated Type 304 stainless steel mean-stress high-cycle fatigue specimens at 1100°F; (c1, c2) $\sigma_a/\sigma_m = 0.72$, (d1, d2) $\sigma_a/\sigma_m = 2.70$. Magnifications 100X.

Figure 33(a). Morphology of fracture in Incoloy-800H mean-stress high-cycle fatigue specimens at 1100°F; (a) stress-rupture specimen loaded at 49.0 ksi, (b1, b2) $\sigma_a/\sigma_m = 1.25$. Magnifications 100X.

Figure 33(b). Morphology of fracture in Incoloy-800H mean-stress high-cycle fatigue specimens at 1100°F; (c1, c2) $\sigma_a/\sigma_m = 2.70$. Magnifications 100X.

Figure 34(a). Morphology of fracture in normalized and tempered 2 $\frac{1}{2}$ Cr-1Mo steel mean-stress high-cycle fatigue specimens at 1000°F; (a) stress-rupture specimen loaded at 34.0 ksi, (b1, b2) $\sigma_a/\sigma_m = 1.60$. Magnifications 400X.

Figure 34(b). Morphology of fracture in normalized and tempered 2 $\frac{1}{2}$ Cr-1Mo steel mean-stress high cycle fatigue specimens at 1000°F; (c1, c2) $\sigma_a/\sigma_m = 4.00$. Magnifications 400X.