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Strainrange Partitioning – A Total Strain Range Version

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STRAINRANGE PARTITIONING - A Total Strain Range Version

by

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ABSTRACT

Procedures are presented for expressing the Strainrange Parititioning (SRP) method for creep-fatigue life prediction in terms of total strain range. Inelastic and elastic strain-range - life relations are summed to give total strain-range - life relations. The life components due to inelastic strains are dealt with using conventional SRP procedures while the life components due to elastic strains are expressed as families of time-dependent terms for each type of SRP cycle. Cyclic constitutive material behavior plays an important role in establishing the elastic strain-range - life relations as well as the partitioning of the inelastic strains. To apply the approach, however, it is not necessary to have to determine the magnitude of the inelastic strain range. The total strain SRP approach is evaluated and verified using two nickel-base superalloys, AF2-1DA and Rene' 95. Excellent agreement is demonstrated between observed and predicted cyclic lifetimes with 70 to 80 percent of the predicted lives falling within a factor of two of the observed lives.

The total strain-range SRP approach should be of considerable practical value to designers who are faced with creep-fatigue problems for which the inelastic strains cannot be calculated with sufficient accuracy to make reliable life predictions by the conventional inelastic strain-range SRP approach.

NOMENCLATURE

- a - Power of time for time-dependent elastic line coefficient
- A - Coefficient of time for time-dependent elastic line coefficient
- b - Power of cyclic life for elastic lines
- B - Coefficient of cyclic life for elastic lines
- c - Power of cyclic life for inelastic lines
- C - Coefficient of cyclic life for inelastic lines
- F - Fraction of inelastic strain
- N - Cyclic life
- t - Time
- Δ - Range of variable
- ε - Strain
- σ - Stress

Subscripts

- el - Elastic
- f - Failure
- ij - pp, cc, cp, or pc
- in - Inelastic
- ob - Observed
- pr - Predicted
- pp - Plastic strain in tension, plastic strain in compression
- cc - Creep strain in tension, creep strain in compression
- cp - Creep strain in tension, plastic strain in compression
- pc - Plastic strain in tension, creep strain in compression
- T - Total

INTRODUCTION

The method of Strainrange Partitioning for predicting high-temperature, low-cycle fatigue lives pioneered a decade ago by Manson, Halford, and Hirschberg (1) is based upon explicit knowledge of the magnitudes of the damaging inelastic creep and plastic strains present in a cycle of loading. Fatigue researchers have given the method widespread evaluation (2) and the concept has found its way into some engineering design procedures for high-temperature components that undergo significant amounts of cyclic inelastic strains (3). However, its use has been hampered in many other practical instances because the magnitudes of the inelastic strains cannot be calculated reliably from nonlinear structural analysis methods. Although progress is being made in improving the accuracy of these analysis tools, there will always remain problems in the computation of inelastic strains because they are too small or because of unreliable or inadequate information such as material properties, temperature distribution and loading history.

For these reasons, considerations have been given to enhancing the manner in which Strainrange Partitioning is applied to the prediction of the lifetime of structural components. The initial approach taken by Manson and Zab (4) for treating low strains and long hold times has been amplified in the present paper. The approach taken is somewhat analogous to that of Manson and Hirschberg in developing the method of Universal Slopes (5) for lower temperature fatigue life prediction.

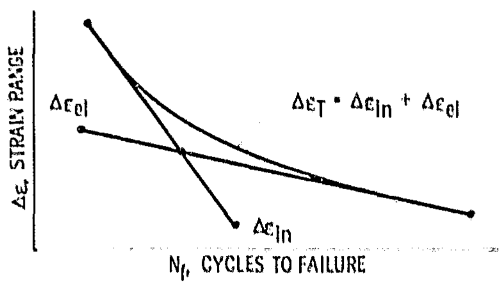

Figure 1. - Schematic total strain range relation as sum of inelastic and elastic components.

They developed the basic Manson-Coffin plastic strain-range power law of low-cycle fatigue into a total strain-range representation by the addition of the elastic and plastic strain-range - life relations as illustrated in Figure 1 and given below:

$$\Delta\varepsilon_T = \Delta\varepsilon_{in} + \Delta\varepsilon_{el} \tag{1}$$

By so doing, they were able to more accurately calculate cyclic lifetimes over a much broader range of strain-ranges and cyclic lives than was possible on the basis of either the plastic strain-range or elastic strain-range alone. The following section describes in general terms the formulation of the proposed total strain-range SRP approach. Subsequent sections deal with detailed aspects of the formulation and finally an evaluation of the approach is presented using published creep-fatigue data on two nickel-base superalloys, AF2-1DA and Rene' 95.

FORMULATION OF APPROACH

Overview

In formulating the current total strain-range approach for SRP, we first determine the conventional inelastic strain-range - life relations for the cycles involving plasticity and creep, i.e., PP, CP, PC and CC type cycles; then the elastic strain-range - life relationships are determined for these same cycles. The problem is more complex than encountered in developing the Universal Slopes elastic strain-range - life relationship, since, at elevated temperatures, the elastic strain (stress) response is not only temperature dependent, but is also time-dependent (as shown schematically in Figure 2) and hence waveshape-dependent. Families of time- and temperature-dependent elastic lines result for every type of inelastic strain cycle and type of

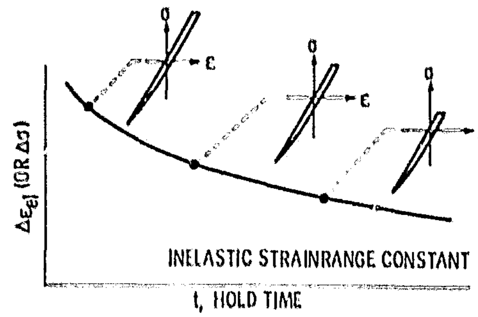

Figure 2. - Trend of decreasing elastic strain range with increasing hold time. Stress hold cycling illustrated. Similar trends evolve for strain hold and slow continuous strain rate cycling.

waveshape (i.e., strain-hold, stress-hold, slow continuous strain rate, etc.). Fortunately, the slopes of these elastic lines have been found, as a first approximation, to be the same as the elastic line slope for pure fatigue cycling with no creep, i.e., PP type cycling. In other words, the principal influence of temperature and time is to shift the $N_f = 1$ intercepts of the elastic lines, as sketched in Figure 3. Equations relating these intercepts to the temperature and time characteristics of stress-strain cycles of interest could, in theory, be derived from reliable cyclic constitutive equations of the material. However, in the absence of appropriate constitutive constants for the materials of interest in the present study, we have had to resort to empirical equations and fit the constants with whatever limited cyclic stress-strain-time-temperature data were available. The form of the equations used will be discussed in a subsequent section.

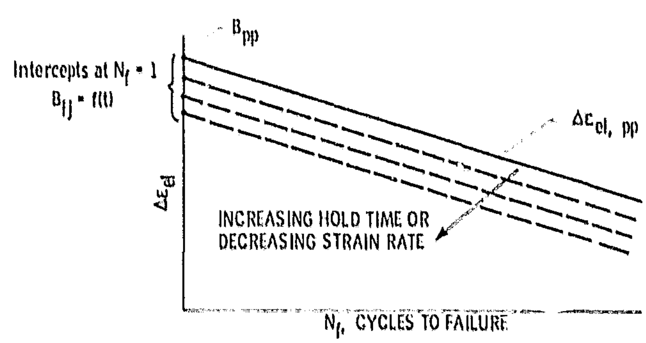

Figure 3. - Schematic representation of time-dependent elastic lines for creep-fatigue loading (CC, PC, or CP).

Having established elastic and inelastic life relationships, they are then available for being added to display families of total strain-range versus life relationships. Identification of the relationships involved is required in making a specific life calculation. This in turn dictates a knowledge of the partitioning of the strain within the cycle of interest, i.e., the determination of the relative amounts of creep and plastic strains. Constitutive behavior theory can be used to partition the relative amounts of creep and plastic strains without having to be concerned with the magnitude or accuracy of the calculated inelastic strain-range of the cycle. The partitioning can be

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accomplished through a knowledge only of the total strain-range, the total strain versus time history within the cycle, the temperature variation within the cycle, and the documented constitutive response characteristics of the material. The actual total strain-range - life relation to be used is the sum of the specific inelastic strain-range - life relation determined using the interaction damage rule in conjunction with the partitioned strain-range fractions and the pertinent elastic strain-range - life relations.

Inelastic Strain Range Considerations

With the aid of Figure 4, we can follow through the steps of the procedure more clearly. To keep the figure as free from confusion as possible, a single temperature is assumed, and a creep-fatigue condition involving only PP and CP strain-range components is considered. Thus only the PP and CP

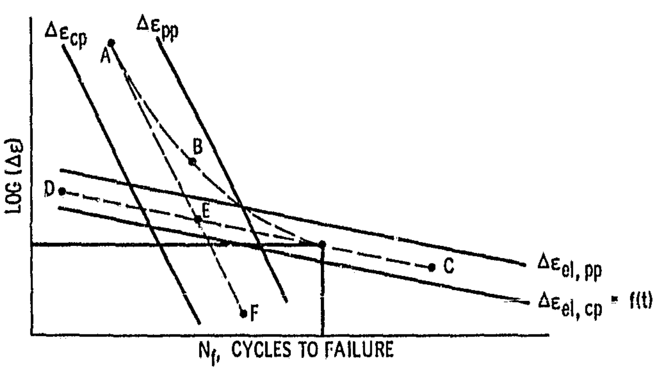


Figure 4. - Schematic total strain range SRP life relation for fixed value of F_{cp}, F_{pp} and cycle shape and time. AEF determined from PP and CP inelastic strain range-life relations using F_{cp} and F_{pp} values and the interaction damage rule. DEC determined from figure 3. ABC is resultant sum of AEF and DEC lines.

inelastic strain-range - life relations are needed for the example. These preferably would be established by direct experiment following the validity guidelines of Hirschberg and Halford (6). Alternatively, the ductility-normalized SRP life relations proposed by Halford and Saltsman (7) could be calculated on the basis of plastic and creep ductility information. For present purposes of keeping the explanation of the procedures as simple as possible, the inelastic life relations are assumed to be independent of high temperature exposure time. Should conditions warrant, however, such complexities could be dealt with in a straightforward manner as discussed in Ref. (7) and by Manson and Zab (8). Also for simplicity, the inelastic SRP life relations are taken to be straight lines on log-log coordinates, and are assumed to be mutually parallel, hence the form:

$$\Delta\varepsilon_{ij} = C_{ij}(N_{ij})^{c} \tag{2}$$

It must be recognized, however, that there is nothing inherent in the SRP framework that requires these life relations be of the form of equation (2). The form is selected herein for simplicity of example and because most data can be represented reasonably in this way.

Mean Stress Effects

Another important aspect of the inelastic strain-range - life relations is the need for their expression in terms of zero mean stress conditions. This concern was first expressed by Halford and Nachtigall (9) while attempting to establish the inelastic strain-range SRP life relations for the nickel-base superalloy AF2-1DA in the low strain-range regime.

All the data used in this study to establish life relations were obtained from fully reversed strain cycles with zero mean strain. However, mean stresses developed in certain cycles due to the imposed wave form of the cycle. PC cycles usually exhibited tensile mean stresses, CP cycles compressive mean stresses, and PP and CC cycles exhibited negligibly small mean stresses. A procedure for accounting for mean stress effects on the SRP life relations was developed by Halford and Nachtigall (9). This procedure was developed for the gas turbine disk alloy AF2-1DA, and it is assumed to apply to Rene' 95 as well.

The reason for applying the procedure is to be able to base the SRP life relations on a hypothetical zero mean stress condition. These SRP life relations, especially in the low-strain, nominally elastic, creep-fatigue regime of current interest, are then more generally applicable. They thus can be used more logically in situations involving mean stresses that are significantly different from those associated with the original test conditions used in developing the life relations. The procedures proposed in Ref. (9) were followed in analyzing all of the data contained in this report.

Elastic Strain Range Considerations

The next step is to determine the elastic line for zero mean stress PP cycling shown in Figure 4 as a straight line on log-log coordinates. In equation form:

$$\Delta\varepsilon_{el,pp} = B_{pp}(N_{pp})^{b} \tag{3}$$

Again, this representation is taken for simplicity purposes and is not an inherent requirement of SRP. In the event experimental data are unavailable, this line might be approximated by the elastic line component from the Method of Universal Slopes (5). Determination of the family of time-dependent and waveshape-dependent elastic lines can be accomplished by several different means: Direct experimental evaluation of low-strain, long-life CP creep-fatigue tests,

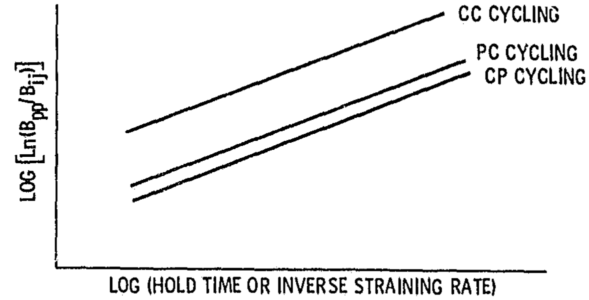


Figure 5. - Trend of time-dependent intercept of elastic lines.

direct experimental determination of the constants in a comprehensive cyclic constitutive behavior theory (for example, Walker's Functional Theory (10) could be used if extended into the small strain regime) followed by a calculation of the elastic strain-range response to any type of creep-fatigue cycle of interest, or finally, as done herein, use of an empirical equation based upon limited creep-fatigue test data.

The form of the representation chosen is shown in Figure 5 wherein a function of the elastic line intercepts for creep-fatigue (and pure fatigue, PP) cycles is plotted versus the cycle hold time (or inverse of strain rate for continuous slow straining cycles) on log-log coordinates. The intercept has been found empirically to be of the form:

$$\mathrm{Ln}(B_{pp}/B_{ij}) = A_{ij}(t)^{a} \tag{4}$$

where B_{pp} is the $N_f = 1$ intercept for PP cycling, B_{ij} is the time-dependent $N_f = 1$ intercept for CP, PC, or CC cycling, t is the hold time of the cycle, and A_{ij} and a are constants that in general would be functions of temperature, type of cycle, and type of waveshape (stress-hold, strain-hold, slow continuous strain rate, etc.). Hence, knowing the characteristics of the cycle of interest (PC, CP, or CC) such as the type of waveshape and the time per cycle, equation (4) will yield the B_{ij} intercept of the pertinent elastic line. Appendix A describes a technique for ascertaining the elastic line intercept for mixed cycles (CC + PC or CC + CP).

There are two aspects of equation (4) that merit discussion: The definition of the hold time factor, t, and the alteration of a material's elastic strain-range response as a result of thermal aging or of other nonrepetitive features such as variable loading levels.

Obviously, the hold time, t, of a cycle, or its frequency, does not sufficiently capture the details of a cycle that are known to influence subsequent stress-strain response and damage per cycle. For example, a given hold time could be interjected either early or late within a cycle and the resultant hysteresis loop would appear quite different. The elastic strain-range would be altered, and the associated damage per cycle would also be affected. With the aid of comprehensive constitutive theories that are currently under development, we should be able to calculate these details with considerably more accuracy than now possible. Furthermore, if the constitutive theories have history-dependent modelling capabilities, then complexities such as thermal aging, large overstrains, and cyclic softening and hardening can also be taken into account when establishing the elastic strain-range response characteristics needed by the total strain-range SRP approach.

An extremely significant advantage of the proposed total strain-range SRP approach is that the cyclic time factor can be dealt with in a rational manner in that the aforementioned details of the time-dependencies within the cycle can be considered explicitly.

Bounding Life

At this stage, the life relations are bounded. The upper bound, of course, is the PP life relation for both inelastic and elastic strain-range components. The sum of these two life relations is the total strain-range versus life curve for pure fatigue (PP) cycling. The lower bound for CP straining is given by the inelastic CP lifeline and the elastic CP lifeline for the longest conceivable time per cycle involved in a problem of interest. Summing these two lower bound curves gives the lower bound total strain-range - life relation. From a first-cut design point of view, life bounds for a given total strain-range may be as far as the analysis has to proceed. However, if more precise calculations of life become necessary, a more refined analysis must be made of the cycle of interest for the purpose of identifying the specific inelastic and elastic lines for summing.

Partitioning

In going beyond the bounding problem, the first requirement is the partitioning of inelastic strains into creep and plastic components in tension and compression. A variety of experimental partitioning techniques have been proposed and discussed by Manson, Halford, and Nachtigall (11) for performing this task. In addition, most cyclic constitutive behavior theories can be adapted to a form for making the needed calculations. To date, constitutive equations have not been developed and evaluated specifically to deal with the very low inelastic strain, nominally elastic, condition being addressed in this paper. It is of special interest, however, to point out that the need herein is only to be able to determine the relative amount of creep and plastic strain, i.e., in the current example, the strain-range fractions F_{cp} and F_{pp}. It is not necessary to determine the actual magnitudes of the inelastic strains. To gain an appreciation of this point, consider that the interaction damage rule (12),

$$1/N_{pr} = F_{pp}/N_{pp} + F_{cp}/N_{cp} \tag{5}$$

can be applied to the PP and CP inelastic strain-range - life relations from a knowledge only of F_{pp} and F_{cp}. For the case in Figure 4 where the PP and CP lines are parallel, a fixed value of F_{pp} and F_{cp} ($= 1-F_{pp}$) in equation (5) along with the PP and CP life relations of equation (2) results in a fixed lifeline AEF that is between and parallel to the PP and CP lines. The equation of AEF is

$$\Delta\varepsilon_{in} = C'(N_f)^{c} \tag{6}$$

$$\text{where } C' = [F_{cp}(C_{cp})^{1/c} + (1-F_{cp})(C_{pp})^{1/c}]^{c} \tag{7}$$

Calculating Life

By adding the inelastic line AEF to the elastic line DEC for the specific cycle of interest, the total strain-range versus life curve, ABC, is obtained. The predicted cyclic lifetime for zero mean stress is then determined directly from ABC by entering with the known value of the total strain-range, $\Delta\varepsilon_T$. The procedures of Ref. (9) are then applied to account for mean stresses present in the cycle under consideration.

The proposed total strain-range SRP approach is intended primarily for extrapolation into the low-strain, long-life, creep-fatigue regime where, because of economic considerations, creep-fatigue testing to determine the constants in the life relations is nearly prohibitive. Any significant amount of creep-fatigue testing can only be accomplished in a higher-strain, shorter-life regime.

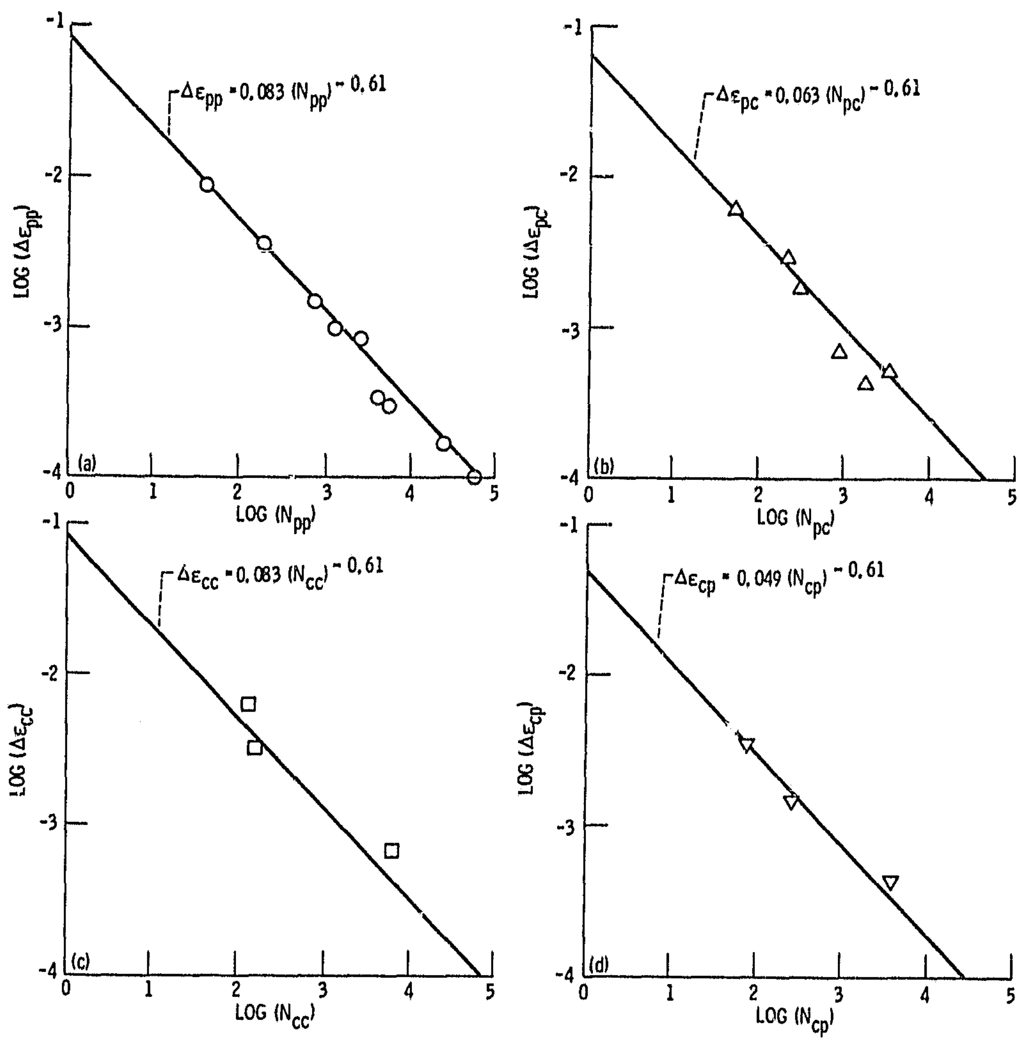
EVALUATION OF APPROACH

In this paper we have evaluated the total strain-range SRP approach using existing creep-fatigue data for two high-strength nickel-base gas turbine disk alloys, Rene' 95 (13, 14) and AF2-1DA (9, 15, 16). The bulk of these data are in the relatively high-strain region with lives of about 10,000 cycles or less. In the evaluation, a series of baseline data is used to determine the necessary material constants, then predictions are made of test results not used in deriving the constants. The results of the evaluation are presented below.

Alloy AF2-1DA at 760° C

The high-temperature, low-cycle, creep-fatigue data used to establish the total strain-range SRP life relations for the alloy AF2-1DA at 760° C were taken from the work of Halford and Nachtigall (9). All of the creep-fatigue data from Ref. (9) were generated at the NASA Lewis Research Center using completely reversed strain tests. Those tests involving creep (CP, PC, and CC) were conducted under stress-hold, strain-limited conditions. Only the completely reversed PP tests used to establish the elastic strain-range versus life relation for PP cycling were performed under strain-controlled conditions.

Since the validity rules for establishing the inelastic strain-range versus life relations were followed in Ref. (9) and since the life relations had been established for a zero mean stress condition, no further analysis was required herein. The life relations given by equations (9) to (12) of Ref. (9) are used directly, i.e.,



(a) PP inelastic line.
(b) PC inelastic line.
(c) CC inelastic line.
(d) CP inelastic line.

Figure 6. - Inelastic SRP life relations for zero mean stress conditions, AF2-1DA, 760° C, Halford and Nachtigall data (9).

$$\Delta\varepsilon_{pp} = 0.083(N_{pp})^{-0.60} \qquad (8)$$

$$\Delta\varepsilon_{cc} = 0.083(N_{cc})^{-0.60} \qquad (9)$$

$$\Delta\varepsilon_{pc} = 0.063(N_{pc})^{-0.60} \qquad (10)$$

$$\Delta\varepsilon_{cp} = 0.049(N_{cp})^{-0.60} \qquad (11)$$

These relations are shown in Figure 6 along with the individual data points used in their establishment.

The elastic strain-range - life relation for PP cycling is shown in Figure 7 and is given by:

$$\Delta\varepsilon_{el,pp} = 0.019(N_{pp})^{-0.10} \qquad (12)$$

The CP, PC, and CC elastic strain-range - life relations are assumed to have the same -0.10 slope, and the intercept values at $N_f = 1$ are represented as a function of the hold time per cycle in these stress-hold tests.

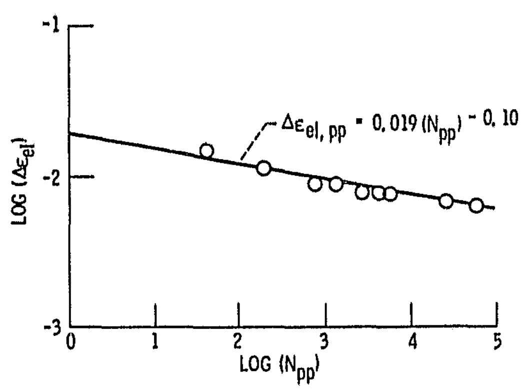


Figure 7. - Elastic strain range - life relation for PP, AF2-1DA, 760° C, Halford and Nachtigall data (9).

Using the form given by equation (4), the constants A_{ij} and a were evaluated by fitting the available data plotted in Figure 8. Since only limited information was available for the evaluation, the straight line curve fit was

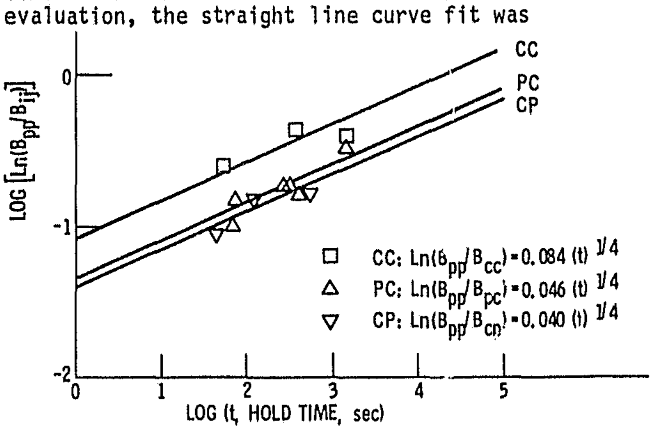
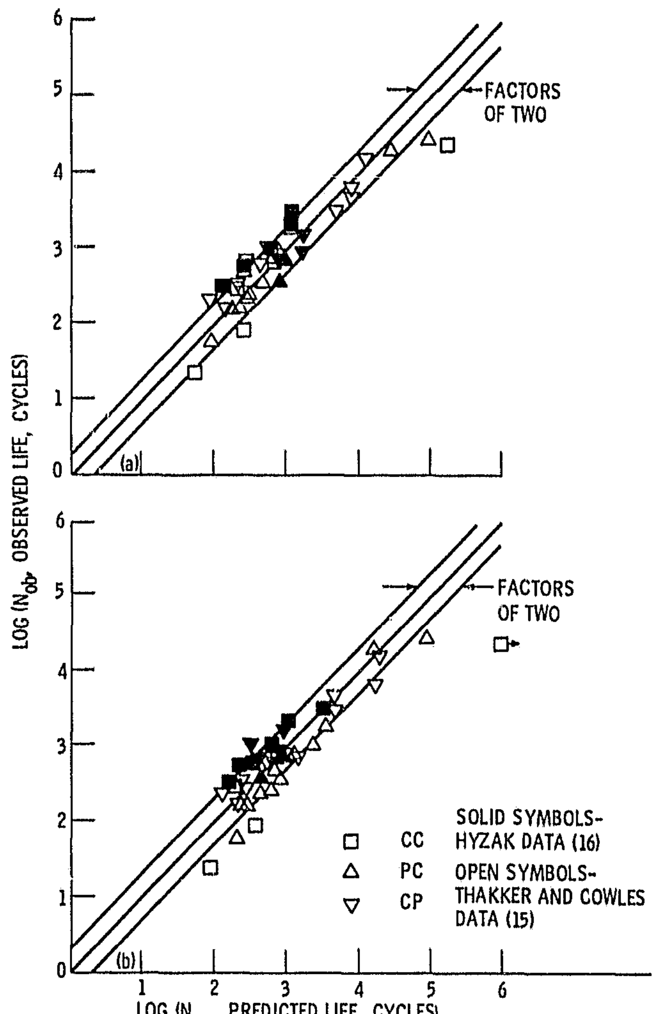


Figure 8. - Time-dependent intercepts for elastic strain range life relations, AF2-1DA, 760° C, Halford and Nachtigall data (9).

accomplished by visual fit and forcing of the three lines to be parallel. A value of $a = 1/4$ fits the common slope reasonably well, and the values of A_{ij} are 0.040, 0.046, and 0.084 for CP, PC, and CC, respectively.

Having obtained the constants for the total strain-range SRP approach for AF2-1DA at 760° C, we can predict the lifetimes of any strain cycle imposed on this alloy at this temperature.

Two sets of data are available for this purpose: Thakker and Cowles (15) under contract to NASA have recently published low-strain, long-life creep-fatigue data for the same heat of AF2-1DA as used to establish the constants in the total strain-range SRP equations, and Hyzak (16) has published data for a different heat of AF2-1DA. All tests were conducted at 760° C and many were strain-hold tests in contrast to the stress-hold tests used to establish the life relations. All of the stress-hold and strain-hold test results were partitioned by visual inspection of the hysteresis loops. Thus, any anelastic strain is lumped with creep rather than with plasticity. In addition, a few continuous slow strain rate cycling test



(a) Total strain range approach.
(b) Inelastic strain range approach.

Figure 9. - Predictability of SRP for AF2-1DA, 760° C.

(0.0033-Hz) results were reported in Ref. (16). We have approximated the partitioning of these tests by assuming equal F_{cc} and F_{pp} values as would have been obtained in a stress-hold test (CC plus PP) of equal cycle duration. Using the NASA baseline tests (9) for the AF2-1DA,

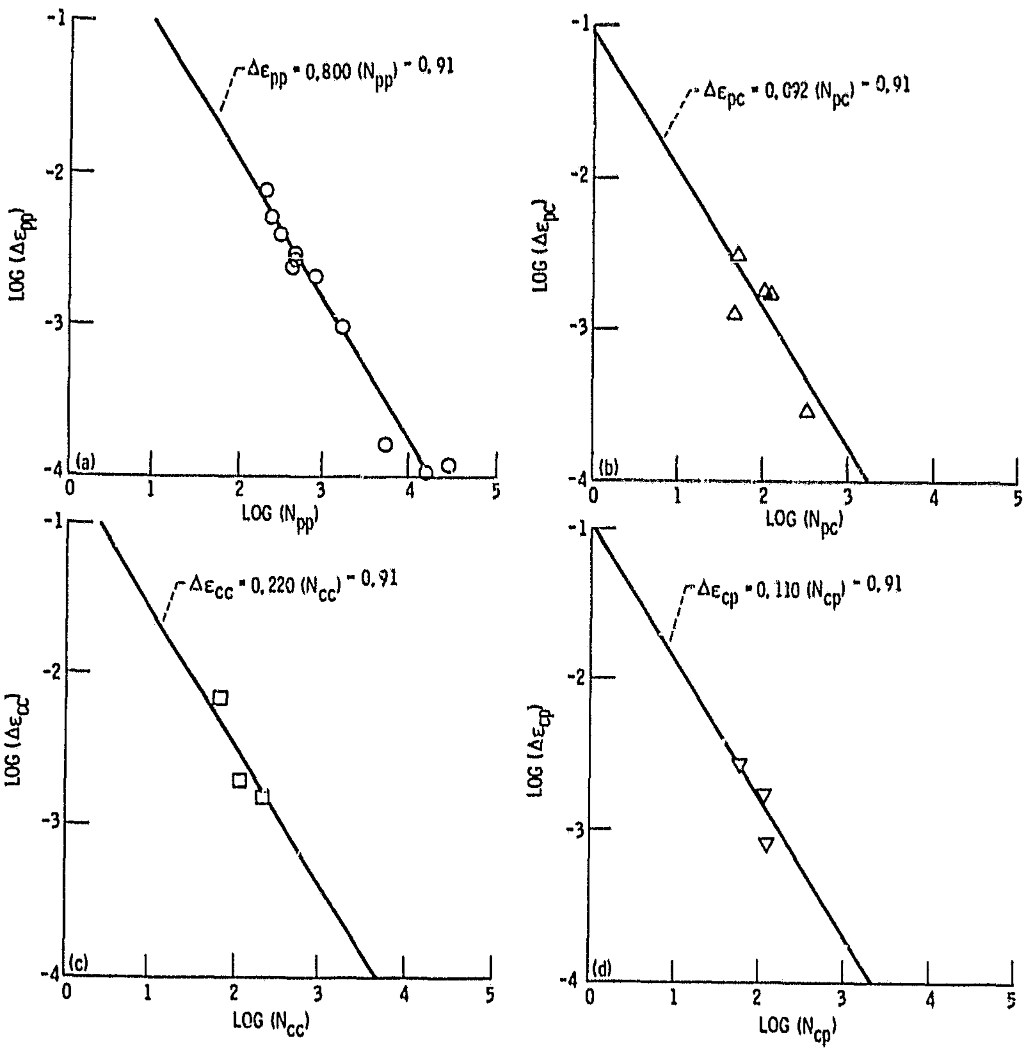
$$F_{cc} = 0.51(t)^{0.054}$$

$$(50<t<1500 \text{ sec, and } 0.7<\Delta\varepsilon_T<1.8 \text{ percent}) \qquad (13)$$

For a 300 second cycle time, $F_{cc} = 0.69$ and hence, $F_{pp} = 0.31$ (since $\sum(F_{ij}) = 1.0$, and $F_{cp} = F_{pc} = 0$ for this test condition).

Results of the life prediction calculations by the total strain-range SRP approach are presented in Figure 9(a) wherein excellent agreement is demonstrated (73 percent of the predicted lives are within a factor of two of the observed cyclic lives). The results are particularly satisfying because the data being predicted involved types of tests and a heat of material that were not used in establishing the baseline constants in the prediction equations. Furthermore, the data shown in Figure 9(a) were obtained in a different laboratory utilizing different experimental equipment and test procedures. This may explain why the CC data of Hyzak (16) systematically fall above those of Thakker and Cowles (15).

As a check against how we would have fared in predicting the lifetimes of the same data using the conventional inelastic strain-range SRP approach, Figure 9(b) was prepared. Not too suprisingly, our ability to predict is nearly as good as shown in Figure 9(a) using the total strain-range SRP approach. This is because the vast majority of the data are for strain-ranges with large enough inelastic components that the inherent limitations (very low strains) of the inelastic SRP approach



(a) PP inelastic line.
(b) PC inelastic line.
(c) CC inelastic line.
(d) CP inelastic line.

Figure 10. - Inelastic SRP life relations for zero mean stress conditions, Rene' 95, 650° C, Hyzak and Bernstein (13) and Bernstein (14) data.

are not encountered. It is expected that as inelastic strain-ranges become too small to accurately calculate or measure, the life predictability by the conventional approach will suffer significantly. This, in fact, is the case in point for the CC test result plotted in Figure 9(b) at an observed life of 2.6×10^4 cycles and a predicted life of 4.4×10^6 cycles. This test had an extremely small inelastic strain-range estimated to be 0.00001 mm/mm, and because of this, the predicted life is highly questionable. If the constants in the total strain approach are carefully established, more accurate life predictions naturally will be expected. In this case, the predicted life based on the total strain-range of 0.005 mm/mm was 1.8×10^5 cycles, in much better agreement with the observed life. However, as pointed out by Manson and Zab (4), it will be difficult, if not impossible, to generate an appropriate data set for fully verifying the total strain-range version of SRP. This is because of the prohibitive expense involved in conducting nominally elastic, low-strain, long-life, creep-fatigue experiments on engineering materials.

Rene' 95 at 650° C

The creep-fatigue results generated by the Air Force on Rene' 95 at 650°C and reported by Hyzak and Bernstein (13) and Bernstein (14) include just enough data meeting the stringent validity requirement of Ref. (6) to establish the inelastic SRP life relations. However, because the CC, CP, and PC data were somewhat sparse, the slopes of these inelastic lines were forced to be equal to the slope of the PP inelastic strain-range - life relation. This appears to be a reasonable assumption as seen in Figure 10 wherein the four life relations and their supporting data are presented. The plotted points have been corrected for any mean stresses present in the original tests, and hence represent a zero mean stress condition. Procedures established for AF2-1DA in Ref. (9) were followed in making the mean stress calculations for Rene' 95.

The elastic strain-range - life relation for PP is displayed in Figure 11 and the equations for the $N_f = 1$ intercepts of the time-dependent elastic lines for CC, PC, and CP are shown in Figure 12. Interestingly, the 1/4 slope used in Figure 12 for Rene' 95 is the same as the slope for the AF2-1DA results of Figure 8. All of the

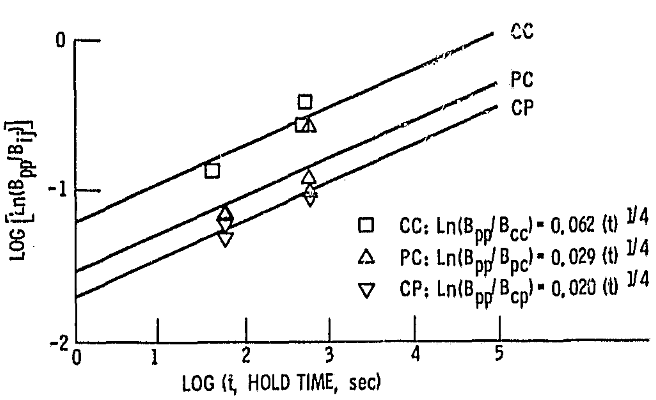


Figure 12. - Time-dependent intercepts for elastic strain range life relations, Rene' 95, 650° C, Hyzak and bernstein (13) and Bernstein (14) data.

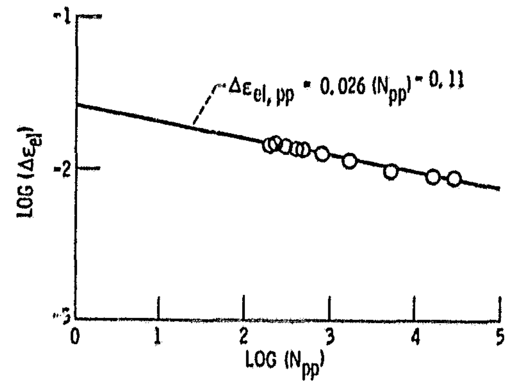


Figure 11. - Elastic strain range - life relation for PP, Rene' 95, 650° C, Hyzak and Bernstein (13) and Bernstein (14) data.

results used in establishing the constants in the inelastic and elastic life relations for Rene' 95 were obtained from strain-controlled tests involving hold periods at the peak tensile strain (CP), at the peak compressive strain (PC), at both the peak tensile and compressive strains (CC), or no hold periods (PP).

Three sets of data for Rene' 95 are available for use in verifying the predictability of the total strain-range SRP method: 1. The strain-hold results of Hyzak and Bernstein (13) and Bernstein (14) that were not used in the establishment of the baseline constants, 2. the verification experimental results from Refs. (13) and (14) for a variety of test cycles (strain-hold, slow continuous strain rate cycling, and dual strain rates, and 3. the stress-hold tests conducted on the same heat of Rene' 95 at NASA and reported by Hyzak and Bernstein (13).

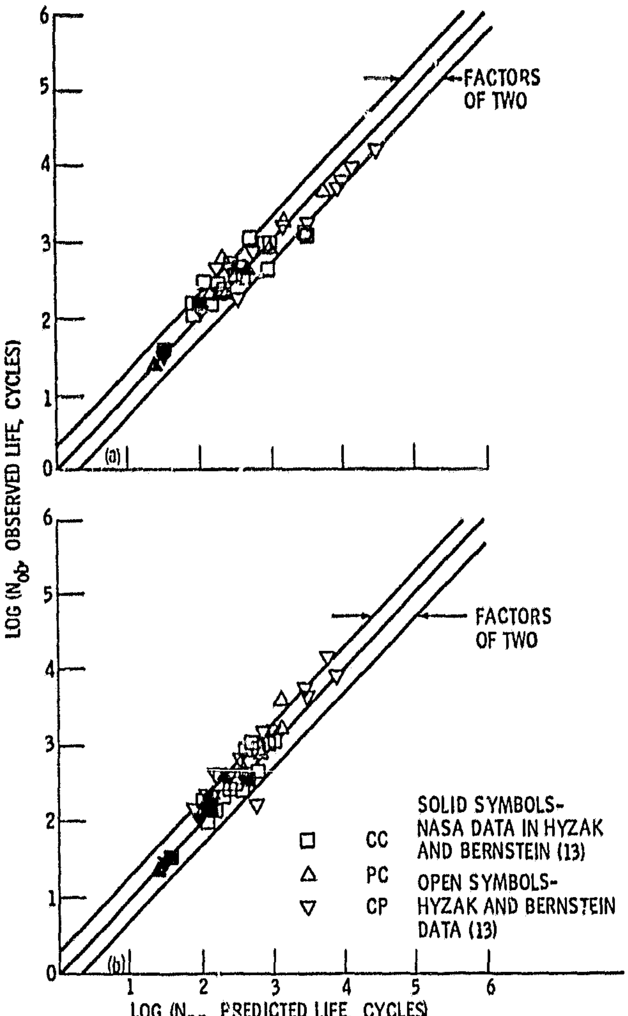
Partitioning of the slow continuous strain-rate cycling tests and the dual strain-rate tests was accomplished by an equation similar to equation (13). However, the partitioning into creep and plastic strain fractions, F_c and F_p, was done on a half-cycle basis (so the dual rate tests could be partitioned properly within each half-cycle), using constants obtained from the stress-hold and strain-hold experiments for which partitioning was self evident from the recorded hysteresis loops.

$$F_c = 0.131(t)^{0.188}$$

$$(250<t<4000 \text{ sec, and } 1.2<\Delta\varepsilon_T<2.5 \text{ percent}) \qquad (14)$$

In the 0.00083-Hz continuous strain cycling tests, t = 600 sec, and $F_c = 0.44$. Therefore, $F_p = 0.56$. Hence, in this case, $F_{cc} = F_c = 0.44$ and $F_{pp} = F_p = 0.56$. For the dual rate experiments, F_c in tension would be different from F_c in compression. To determine the values of F_{cc}, F_{cp} (or F_{pc}) and F_{pp}, the rules of Strainrange Partitioning outlined in Ref. (1) are to be followed.

Life predictions of the Rene' 95 data are compared with the observed lives in Figure 13(a) for the total strain-range SRP version and in Figure 13(b) for the conventional inelastic approach. Again, the agreement of the predictions



(a) Total strain range approach.
(b) Inelastic strain range approach.

Figure 13. - Predictability of SRP for Rene' 95, 650° C.

with the observed lives is quite good for the total strain-range SRP version with 81 percent of the data being predicted to within factors of two. Predictions by the conventional inelastic SRP version are still quite reasonable, but with only 70 percent of the data falling within a band of factors of two of the observed lives.

CONCLUDING REMARKS

Following up on the pioneering low-strain, long hold time SRP work of Manson and Zab (4), we have developed a set of workable and generally applicable procedures for casting the SRP method of creep-fatigue life prediction in terms of total strain-range versus cyclic life. In this form, the approach should be of much greater value in the prediction of the cyclic lifetime of engineering structures that operate in severe high temperature environments. This enhanced capability of the SRP method quite naturally requires a greater degree of material characterization than with the conventional inelastic strain-range version. However, the added material constants are, in theory, derivable from cyclic constitutive response behavior. Such behavior is attainable experimentally even for long times per cycle, whereas cycles-to-failure data based on the same cycle times would be nearly prohibitively expensive to obtain. The approach we have taken permits the realistic calculation of long lives without having to conduct long-time, creep-fatigue tests to failure.

Although a thorough calibration and verification of the total strain-range SRP approach may be difficult, and extrapolations in time and cycles must be relied upon, it is important to keep in mind that the rationale used in evolving the approach is realistic and qualitatively consistent with how most materials behave during creep-fatigue loading.

To date, very few creep-fatigue data have been generated that could be used in a critical evaluation of the proposed approach. Obviously, a true verification must await the availability of additional, expensive, long-time, low-strain creep-fatigue data. Partial verification, nevertheless, has been provided by data available in the literature for the gas turbine disk alloys, AF2-1DA and Rene' 95.

An extremely desirable aspect of any high-temperature, creep-fatigue life prediction approach is its applicability to the problem of thermal-mechanical strain cycling. Because of the manner in which the total strain-range SRP version has been cast (i.e., inelastic strain and its type--plastic or creep--essentially dictates failure behavior, whereas the amount of each type of strain and the amount of the elastic strain are quantities dictated by the flow behavior), it can be applied to any generalized thermal-mechanical cycle that could have been handled via the conventional inelastic strain-range SRP version. To date, there have been but limited attempts to address thermal-mechanical fatigue using conventional SRP methodology. In the first attempt (17), we dealt with a material (Type 316 stainless steel) whose inelastic SRP life relations were independent of temperature, and thus the problem was greatly simplified. In the most recent attempt (18), a realistic thermal fatigue cycle for a gas turbine blade was addressed. The material, Rene' 80, exhibited complex behavior, and it was necessary to consider how the inelastic SRP life relations varied with temperature. In both cases, the procedures employed for predicting life were straightforward, and the use of the current total strain-range SRP version would present no known difficulties provided the constitutive response characteristics were known for the temperature ranges studied. In fact, when dealing with a variable temperature problem, it should be necessary to determine the elastic strain-range - life relations only for the temperatures corresponding to the two extremes of strains of the cycle. Specific procedures for analyzing thermal fatigue cycles, however, are beyond the scope of the present paper, which has addressed isothermal conditions.

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APPENDIX A

Elastic Line Intercept for Mixed CC + CP or CC + PC Cycles

In the approach outlined in the body of this paper, we have modeled the time-dependency of the elastic lines associated with either CP, PC, or CC type loading cycles. An important question arises as to how to model the elastic line when either CC + CP or CC + PC type loadings are present. If the constitutive relations and their constants are known, this question can be answered in the same manner as it was in establishing the CP, PC, or CC elastic lines directly from constitutive behavior. The question is pertinent primarily when the elastic lines have been established empirically from individual CP, PC, or CC type tests.

As a first approximation, we have assumed the two elastic lines (CC + CP or PC) of interest are weighted in accordance with the amount of time per cycle that can be associated with the CC and CP or PC strain-ranges, t_{cc} and t_{cp} or t_{pc}, respectively. For example, if a tensile hold time exceeds the compressive hold time by four to one, i.e., 4 minutes in tension and 1 in compression, then we would associate 2 minutes of time with CC (1 minute each in tension and compression) and the remaining 3 minutes of time in tension with CP. Once the two appropriate intercepts, B_{cc} and B_{cp}, are thusly determined, the intercept value to use in the life prediction is the weighted average of the two, i.e.,

$$B = [(t_{cc})B_{cc} + (t_{cp})B_{cp}]/(t_{cc} + t_{cp}) \qquad (15)$$