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LIFE PREDICTION OF THERMAL-MECHANICAL FATIGUE USING STRAINRANGE PARTITIONING

by G. R. Halford
Lewis Research Center
Cleveland, Ohio 44135

and

S. S. Manson
Case Western Reserve University
Cleveland, Ohio 44106

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G. R. Halford, Lewis Research Center, Cleveland, Ohio

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ABSTRACT: This paper describes the applicability of the method of Strainrange Partitioning to the life prediction of thermal-mechanical strain-cycling fatigue. An in-phase test on 316 stainless steel is analyzed as an illustrative example. The observed life is in excellent agreement with the life predicted by the method using the recently proposed Step-Stress Method of experimental partitioning, the Interaction Damage Rule, and the life relationships determined at an isothermal temperature of 705° C. Implications of the present study are discussed relative to the general thermal fatigue problem.

KEY WORDS: thermal fatigue, intergranular fracture, plastic strain, creep strain, life prediction, strainrange partitioning, stainless steel

Several of the papers at this Symposium relate to fatigue data obtained under thermal-mechanical strain-cycling involving the simultaneous independent variation of both strain and temperature. Recently, we have been studying a method for treating high-temperature fatigue which we feel is very well suited to such problems. We have termed the method Strainrange Partitioning because it involves the partitioning of the inelastic strainrange imposed during the cycle into from one to four generic strainranges. These are associated with the manner in which "creep" and "plasticity" interact during the tensile and compressive halves of the cycle. Several features of the method are of special advantage in the treatment of thermal-mechanical cycling. The purpose of this paper is briefly to summarize these features, and to illustrate by an example how the method is applied.

SPECIAL FEATURES OF THE STRAINRANGE PARTITIONING METHOD

The method has been described in references (1-4)*. Therefore the full description of the principles involved and the procedures to be followed will not be repeated here. However, to place the method in proper perspective in relation to the analysis of thermal-mechanical cycling of interest to this Symposium, it is relevant to summarize several features of the method.

The basic procedure involves the partitioning of the hysteresis loop into its creep and plasticity components in both the tensile and compressive halves of the cycle. From these components, the generic strainranges, $\Delta\epsilon_{pp}$, $\Delta\epsilon_{pc}$ $\Delta\epsilon_{cp}$, and $\Delta\epsilon_{cc}$ can be readily calculated, where,

$\Delta\epsilon_{pp}$ = tensile plastic strain that is balanced by compressive plastic strain

$\Delta\epsilon_{pc}$ = tensile plastic strain that is balanced by compressive creep strain

*Numbers in parenthesis refer to the list of references appended to this paper.

$\Delta\varepsilon_{cp}$ = tensile creep strain that is balanced by compressive plastic strain

$\Delta\varepsilon_{cc}$ = tensile creep strain that is balanced by compressive creep strain.

Methods for conveniently carrying out the partitioning process have recently been developed (4). Although the application in the past has been for isothermal straining, the same procedures can readily be applied when the temperature is changing during the cycle, as will be discussed later in the paper. While the method can be used to treat a variety of high temperature fatigue problems, it contains several features that are especially attractive in relation to thermal-mechanical applications:

a) Accounts for Details of Cycle, Including Compressive Stress

A special aspect of Strainrange Partitioning that is relevant to the subject of thermal fatigue analysis is that it is possible to distinguish between the severity of the different types of strainranges that can commonly be generated during such cycling. For example, if the strain is "in-phase" with the temperature (rising tensile strain while temperature is increasing), the strainrange will likely include a $\Delta\varepsilon_{cp}$ component. "Out-of-phase" cycling (rising compressive strain with increases in temperature) is conducive to the development of a $\Delta\varepsilon_{pc}$ component of strainrange. In no case can a cycle include both a $\Delta\varepsilon_{cp}$ and a $\Delta\varepsilon_{pc}$ component. Since the method associates different effects with each of these strainrange types, it not only provides a means for recognizing the importance of the compressive portion of the cycle (which some alternative methods do not, for example, that currently specified by the ASME Boiler and Pressure Vessel Code Case 1592 (5)), but it also provides a basis for distinguishing between the details of the cycle that can have effects on fatigue life.

b) Avoids Ambiguity Regarding Effect of Temperature on Life Relations

Once the hysteresis loop has been partitioned, and the pertinent components of strainranges $\Delta\varepsilon_{pp}$, $\Delta\varepsilon_{cc}$ and $\Delta\varepsilon_{cp}$ or $\Delta\varepsilon_{pc}$ determined, the method makes use of an Interaction Damage Rule (2) to combine the effects of two or three strainranges present. In applying the rule, the life relations for each component strainrange become the important material characterization parameters. It has been found that for 316 stainless steel (and 2 1/4 Cr-1 Mo steel) the life relationships are essentially independent of temperature (3). This feature bestows a distinct advantage to the method because it removes the ambiguity of determining which temperature within the spectrum covered by temperature variation throughout the cycle is the important one for the choice of pertinent life relation. Of course, temperature is in itself important, because the temperature not only governs the strainrange imposed, but it influences how much of the imposed strainrange is absorbed as $\Delta\varepsilon_{pp}$, $\Delta\varepsilon_{pc}$, $\Delta\varepsilon_{cp}$ and $\Delta\varepsilon_{cc}$. The higher the temperature, the more likely an input inelastic strain is absorbed as creep rather than as plasticity. But for a given magnitude and type of strainrange, the life is essentially independent of the temperature.

c) Provides Upper and Lower Bounds on Life

The method lends itself especially well to the determination of bounding values on life. Thus, once the strainrange is known, a lower bound on cyclic life can be obtained by assuming that all of the strainrange present is of the most damaging type (for most materials, $\Delta\varepsilon_{cp}$, but for some, $\Delta\varepsilon_{pc}$). An upper bound on life can likewise be determined by assuming that the entire strainrange is of the most benign type ($\Delta\varepsilon_{pp}$). If the bounding values are acceptable, a detailed analysis to determine the actual hysteresis loops and to partition them in detail becomes unnecessary; if not, the need for a more detailed study is indicated. This feature had special merit to designers who may wish to apportion design effort according to the needs of a particular situation, rather than making detailed analyses. It is also of special value to Code bodies in specifying under what conditions minimal analyses will be required (i.e., when the most pessimistic estimate of life associated with the lower bound can be tolerated), and when detailed analyses are needed (i.e., when the designer is motivated to take full advantage of the potential life of the part).

AN EXAMPLE ANALYSIS

As a demonstration of the applicability of the method of Strainrange Partitioning to the thermal-mechanical strain-cycling problem, an axially loaded tubular test specimen as described in Ref. (6) was subjected to the test listed in Table I.

The cyclic test was interrupted occasionally throughout its life of 307 cycles to failure in order to apply the Step-Stress

Method (4) to partition the creep and plastic strain. A hysteresis loop, typical of the stabilized thermal-mechanical condition, is reproduced in Fig. 1 showing the selected step-stress levels (points C through K of loop A through K). The temperature is at a peak of 760^{o} C at point G and is at a minimum of 230^{o} C at point A.

Step-Stress Partitioning

The partitioning procedure followed is to halt temporarily the temperature and strain programmers at a selected point such as C, switch the servo-controller from strain to load control and hold the stress and temperature constant at the stabilized values associated with point C while the creep strain is measured as a function of time. This condition is held until a steady-state creep rate can be established. At point C', the controller is switched back to strain control and the strain and temperature programs are resumed. Before stopping at the next step-stress level, the hysteresis loop is restabilized by traversing another one or two cycles.

From the creep rate information measured at the various stress and temperature levels, a plot is made of the steady-state creep rate versus time for one complete cycle. Figure 2 was constructed for the cycle of interest. The integrated area under the steady-state creep rate versus time curve is equal to the steady-state creep strain accumulated within the cycle. Following the suggestion of Ref. (4), the steady-state creep strain is taken as the significant "creep" strain and all of the other inelastic strain is considered to be "plastic". For the case at hand, the compressive steady state creep strain is 0.00006. Since the compressive inelastic strain is 0.00616 and the creep strain is 0.00006, the plastic strain in compression is 0.00610. Similarly, the tensile creep strain from Fig. 2 is 0.00145 and the compressive plastic strain is 0.00471. Hence, the partitioned strainranges (1) are:

$$\Delta\varepsilon_{pp} = 0.00471,\ \Delta\varepsilon_{cc} = 0.00006,\ \Delta\varepsilon_{cp} = 0.00139$$

where:

$$\Delta\varepsilon_{in} = \Delta\varepsilon_{pp} + \Delta\varepsilon_{cc} + \Delta\varepsilon_{cp} = 0.00616$$

The strainrange fractions for use in the Interaction Damage Rule (2) are:

$$F_{pp} = \Delta\varepsilon_{pp}/\Delta\varepsilon_{in} = \frac{0.00471}{0.00616} = 0.765$$

$$F_{cc} = \Delta\varepsilon_{cc}/\Delta\varepsilon_{in} = \frac{0.00006}{0.00616} = 0.010$$

$$F_{cp} = \Delta\varepsilon_{cp}/\Delta\varepsilon_{in} = \frac{0.00139}{0.00616} = 0.225$$

Prediction of Thermal-Mechanical Strain-Cycling Life

The partitioned strainrange life relationships for 316 stainless steel have been reported previously (1) for use with the Linear Damage Rule and have also been shown (3) to be essentially independent of test temperature. Hence, these relationships are ideally suited for application to the life prediciton of the thermal-mechanical strain cycle under consideration. However, these earlier relationships do not account for the newest interpretation of creep strain (i.e., using only the steady-state component) nor for the use of the new Interaction Damage Rule.

Saltsman and Halford (7) have recently reported the partitioned strainrange versus life relationships for 316 stainless steel for use with the Interaction Damage Rule. To be consistent within this paper these relationships have been modified to include the new interpretation (4) of creep strain as being only the steady-state component. Hence, for an inelastic strainrange of 0.00616, the N_{pp}, N_{cc}, and N_{cp} lives are 1330, 405, and 94 cycles respectively. The predicted life N_{pr} is computed from the Interaction Damage Rule (2) as follows:

$$\frac{F_{pp}}{N_{pp}} + \frac{F_{cc}}{N_{cc}} + \frac{F_{cp}}{N_{cp}} = \frac{1}{N_{pr}}$$

$$\frac{.765}{1330} + \frac{.010}{405} + \frac{.225}{94} = \frac{1}{N_{pr}}$$

$$.000575 + .000025 + .002395 = .002995 = \frac{1}{N_{pr}}$$

$$N_{pr} = 334$$

Agreement between the predicted (334) and observed (307) lives is excellent in this case.

Bounding the Life Values

An alternative approach here, instead of quantitatively determining life by detailed partitioning, is to estimate bounding values on life from a knowledge of the total inelastic strainrange and an estimate of the types of strainrange likely to be present. Here, because of the nature of the cycling, the most damaging type of strainrange is of the $\Delta\varepsilon_{cp}$ type. If the entire cycle produced a $\Delta\varepsilon_{cp}$ type strainrange, the life would be 94 cycles to failure. Thus, this value is a lower bound on life. Its value is determined without detailed partitioning. Had the test been of the "out-of-phase" type, the lower bound on life would have been 410 cycles (i.e., the life if the strainrange were entirely of the $\Delta\varepsilon_{pc}$ type). In both cases, the upper bound on life would have been the N_{pp} value of 1330 cycles to failure.

Some Metallurgical Aspects

As was shown in Ref (1), application of a $\Delta\varepsilon_{cp}$ type strainrange is conducive to intergranular creep cracking in 316 stainless steel. The photomicrographs of the failed specimen shown in Fig. 3 also reveal intergranular cracking (particularly evident in Fig. 3a), thus substantiating qualitatively the measured presence of a significant amount of this type strainrange in the present test. Figure 3c shows the wall thickness of the tubular specimen on the side of the tube from which the major crack originated and propagated. This cracking was along grain boundaries. Intergranular secondary cracks are also noted, although there is an indication that these were initiated in a transgranular mode, possibly by the action of the pp type component of strainrange. Figure 3b is a photomicrograph of the wall thickness on the opposite side of the tube. The 45 degree shear angle across the thickness illustrates the final tearing-off of the specimen into two pieces on the 307th cycle This tearing action opened up a number of internal intergranular cracks that had formed during the thermal-mechanical strain-cycling. It should be noted that the failed specimen is free of cycle-dependent buckling or other geometric instabilities (Fig. 3d) such as discussed by Coffin (8) at this Symposium.

CONCLUDING REMARKS

We have presented in this paper details of how the method of Strainrange Partitioning would be applied to a thermal-mechanical strain-cycling problem. Extension of the method to an actual thermal fatigue problem would not be a difficult task provided an analysis were available to indicate the temperature and strain versus time histories of the cycle of interest. An axially loaded laboratory specimen could then be programmed to follow these temperature and strain histories. The specimen would respond to give the magnitude of the inelastic strainrange and the stress (and thus the steady-state creep rate) as a function of time. From that point on, the determination of the creep and plastic strains, the partitioned strainrange components, etc. would follow the procedures described in this paper. As an alternative to experimental partitioning, constitutive equations representative of cyclic behavior could be determined for the material over the temperature range covered, and an analytical partitioning could be applied. However, this is a subject for a future paper. Of course, bounds on cyclic life can be established without having to resort to either experimental or analytical partitioning.

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TABLE I Specimen and Test Procedures used for Example Problem

Material: AISI Type 316 stainless steel, fully annealed

Specimen: Tubular, hour-glass test section (6)

Strain: Diametral extensometer, diametral strain cyclically ramped linearly with time between limits resulting in an axial total (mechanical) strainrange of 0.00923. The resultant inelastic strainrange was 0.00616. The cycle period was 30 minutes.

Temperature: Silicon carbide internal heating element, temperature ramped linearly with time between temperature limits of 230 and 760^{o} with a period of 30 minutes. The temperature was phased with the strain such that the maximum temperature occurred at the peak tensile strain. This is referred to as an "in-phase" thermal-mechanical strain cycle.

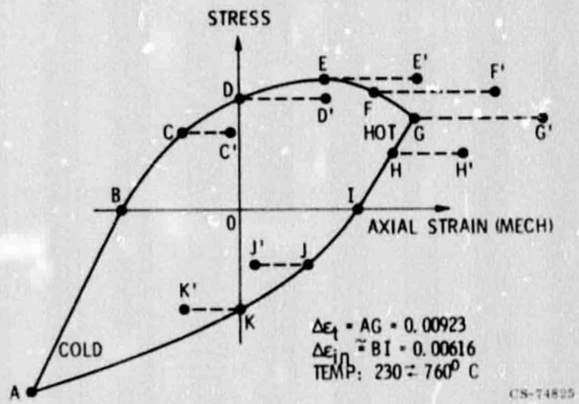

Figure 1. - Mechanical stress-strain hysteresis loop for thermal-mechanical strain cycle illustrating stress levels used for partitioning strains.

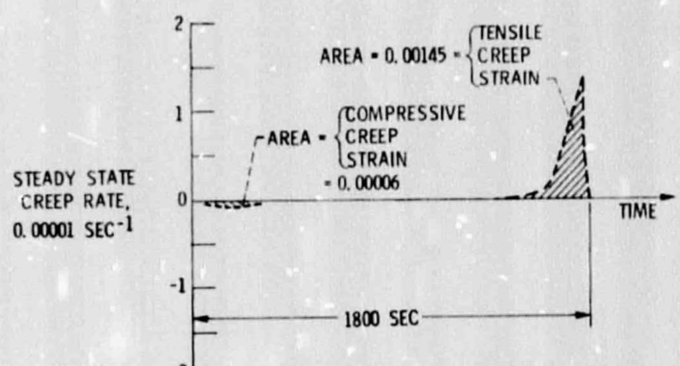

Figure 2. - Accumulation of tensile and compressive creep strain during thermal-mechanical strain cycle 230 ⇄ 760° C) for 316 stainless steel.

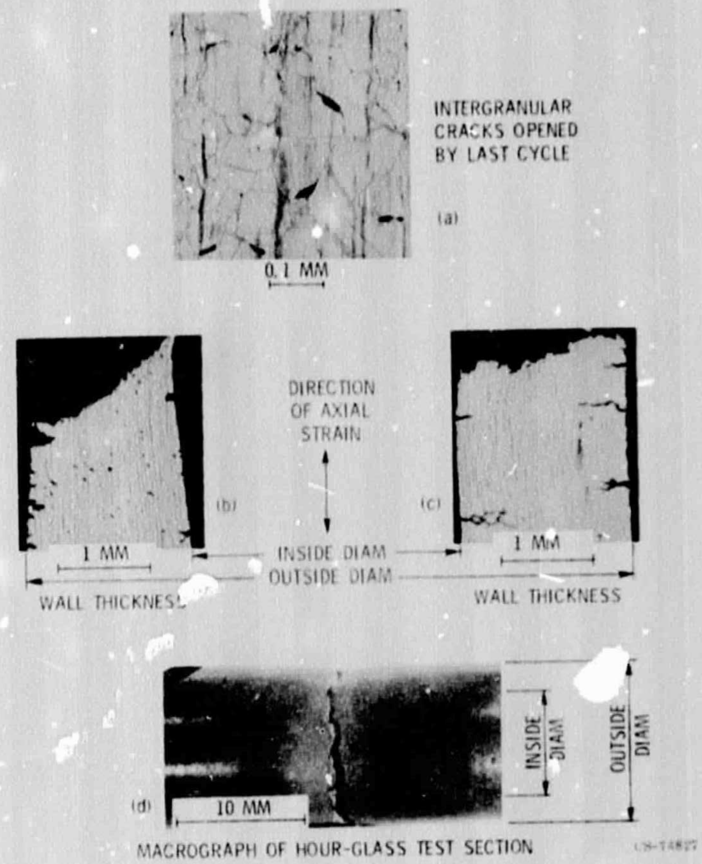

Figure 3. - Photomicrographs of failed specimen of 316 stainless steel subjected to thermal-mechanical strain cycling, 230 ⇄ 760° C, in-phase.