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STRAINRANGE PARTITIONING - A TOOL FOR CHARACTERIZING HIGH-TEMPERATURE LOW-CYCLE FATIGUE

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ABSTRACT

The basic concepts of Strainrange Partitioning are reviewed and the areas requiring expanded verification are detailed. A suggested cooperative evaluation program involves the verification of the four basic life relationships (for PP, CC, PC, and CP type inelastic strainranges) for a variety of materials that are of direct interest to the participating organizations.

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SUMMARY

The Strainrange Partitioning approach to high-temperature low-cycle fatigue has been undergoing development at the NASA-Lewis Research Center since its introduction four years ago. The concept has been developed to the point where we are confident of its capabilities and are enthusiastic about the promise the approach holds for materials specialists and designers who are in a position to take advantage of its attributes. Our enthusiasm stems largely from the fact that Strainrange Partitioning is based upon a simple concept with fundamental soundness and that it can be adapted to handle any conceivable cyclic straining fatigue problem. We feel it is the most versatile and most easily applied approach currently available. However, we recognize that acceptance of Strainrange Partitioning by others hinges largely upon a broader verification of the approach and this involves application to a wide variety of materials by a number of independent laboratories. A cooperative evaluation program is therefore proposed which would have the objective of achieving this broader verification through

the additional experience provided by the participants in the program.

The basic concepts of Strainrange Partitioning are reviewed and the areas requiring expanded verification are detailed. The suggested program involves the verification of the four basic life relationships (for PP, CC, PC, and CP type inelastic strainranges) for a variety of materials that are of direct interest to the participating organizations. Once determined, the four relationships would be used in conjunction with the Interaction Damage Rule to predict the cyclic lives of tests involving various combinations of the basic strainrange components. Evaluation of the degree of insensitivity of these relationships to temperature as well as their utility in representing bounds on life, is also included in the suggested testing program.

INTRODUCTION

The authors suggest a cooperative evaluation program that would provide a broader based verification of the Strainrange Partitioning Method for dealing with high-temperature, low-cycle fatigue. The program is in keeping with a basic mission of AGARD to recommend effective ways for the member nations to use their research and development capabilities for the common benefit of the NATO community. Strainrange Partitioning offers a unifying approach to high-temperature fatigue and the NATO nations could share in its future development to the common benefit of all.

In considering how to organize such a cooperative effort, a number of alternatives were scrutinized. It was decided that the greatest benefit would result from a program wherein each participating organization would evaluate Strainrange Partitioning on a material of their choice. In this way, a variety of important engineering materials could be characterized and a broader base would be established for the critical evaluation of this promising new method. The suggested program concentrates on four of the most important facets of Strainrange Partitioning. In particular, it addresses the questions of a) whether the fatigue-creep behavior of each material can be represented by four independent strainrange versus life relationships as implied by the method. b) Do the life relationships represent bounds on cyclic life? c) Are these relationships relatively independent of temperature of testing? d) Can complex strain cycles be partitioned into their basic component strainranges, and can the ensuing cyclic lives be accurately predicted within the framework of the method? Details of the program will be presented following a brief review of the fundamantal aspects of Strainrange Partitioning.

AGARD has recognized the technological and economic desireability of seeking out common solutions to the problems associated with high-temperature fatigue by establishing in 1971 a Working Group on Low-Cycle, High-Temperature Fatigue. Subsequently, J. M. Drapier (ref. 1) of Belgium prepared an extensive survey of the activities in the field of low-cycle, high-temperature fatigue among 38 laboratories in 7 NATO nations. His excellent report was presented at a 1973 Structures and Materials Panel Meeting nearly two years ago. An outstanding impression gained from studying his report is the feeling that much of the effort devoted to high-temperature low-cycle fatigue research is diverse and lacking in unanimity of approach. Various fatigue life prediction approaches were therefore the subject of active discussion at a 1974 Specialists Meeting held in Washington D.C. (ref. 2). It was the intense interest expressed at that time that has prompted this paper in which the authors propose a cooperative evaluation program centering on the Method of Strainrange Partitioning which we feel has the potential to unify the field of high-temperature, low-cycle fatigue.

REVIEW OF STRAINRANGE PARTITIONING CONCEPTS

At the NASA-Lewis Research Center we have long been involved in the development of theories and approaches for dealing with low-cycle fatigue behavior of materials. A most important transition from a stress approach to a strain approach occurred with the formulation of the Manson-Coffin Law (ref. 3). We then went to the total strain approach with the inclusion of the elastic portion of the total strainrange (ref. 4). The Manson-Hirschberg Method of Universal Slopes was then developed (ref. 5) which made it possible to estimate total strainrange-life behavior from conventional short-time tensile properties. It was of course recognized that the above approaches were all limited to temperatures below the creep limit. Our first attempts to account for creep effects were the 10% rule (ref. 6) and the creep-modified 10% rule (ref. 7). These approaches represented most of the available elevated temperature test data rather well, but they were not sufficiently conservative for cases involving long hold times or where large creep strains could be accumulated. An attempt to remedy this was made with the Life Fraction approach (ref. 8). Unfortunately, this latter method involves extensive analytical procedures and was unable to explain some of the experimental observations regarding the damaging effects of compressive stress. The next step was the formulation of the Method of Strainrange Partitioning which holds promise for overcoming deficiencies in previous methods.

The basic premise for Strainrange Partitioning, as set forth in reference 9, is that in any hysteresis loop there are combinations of just two directions of straining and two types of inelastic strain. The two directions are, or course, tension and compression while the two types of inelastic strain are either of a time-dependent nature (creep) or of a time-independent nature (plastic). By combining the two directions with the two types of strain, we arrive at four possible kinds of strainranges that may be used as basic building blocks for <u>any</u> conceivable hysteresis loop. These define the manner in which a tensile component of strain is balanced by a compressive component to close a hysteresis loop and are described as follows:

1) Tensile <u>p</u>lasticity reversed by compressive <u>p</u>lasticity is designated a PP strainrange and represented by $\Delta\epsilon_{pp}$.

2) Tensile <u>c</u>reep reversed by compressive <u>p</u>lasticity is designated a CP strainrange and represented by $\Delta\epsilon_{cp}$.

3) Tensile <u>p</u>lasticity reversed by compressive <u>c</u>reep is designated a PC strainrange and represented by $\Delta\epsilon_{pc}$.

4) Tensile <u>c</u>reep reversed by compressive <u>c</u>reep is designated a CC strainrange and represented by $\Delta\epsilon_{cc}$.

The notation used for the subscripts for the strainranges defines the tensile type strain first, followed by the compressive type strain. The name Strainrange Partitioning was chosen because it represented our premise that in order to handle a complex high-temperature low-cycle fatigue problem, the inelastic strainrange must first be partitioned into its components as listed above.

A graphical representation of the four component strainrange-life relationships is shown in figure 1. What we have proposed then, is that the Manson-Coffin relationship for representing the inelastic strainrange-life behavior for materials below the creep limit be expanded to four separate relationships for dealing with materials above the creep limit. It should be noted that the PP relationship is in effect identical to the original Manson-Coffin relationship since no creep strain is present.

Before we can use these four life relationships, we must first find a way to experimentally produce them. Figure 2 shows types of idealized hysteresis loops that could be used to generate the desired failure curves. The PP type hysteresis loop (fig. 2a) can be generated in a conventional manner but the other three, as shown in figures 2b, 2c, and 2d require some less-conventional testing procedures. Detailed procedures for generating the required data for utilizing the Method of Strainrange Partitioning will be described in the section "Suggested Evaluation Program".

Once the curves that are schematically represented in figure 1 have been generated, there remains the question of how to apply these curves to a complex problem in order to predict life. This is accomplished in two parts. First, it is necessary to know the hysteresis loop for the cycle being analyzed and be able to partition the loop into its inelastic components. Second, a damage rule must be applied in order to predict the life associated with a combination of applied strainranges.

Figure 3 is a schematic representation of a complex hysteresis loop. This loop is made up of the following loading sequences. Starting at point 1, we load rapidly to point 2 and then hold the stress constant until we reach point 3. We then unload elastically to point 4 and continue on rapidly to point 5. We then hold the compressive stress constant until we reach point 6, at which time we hold the strain constant and relax the stress to point 7. The cycle is completed by unloading elastically to point 1 where the cycle started. In the loop being described, the inelastic strainrange is defined by the width of the loop AC. In going from A to C in the tension direction, we accumulated a tensile plastic strain AB and a tensile creep strain BC. In reversing the cycle, we accumulated a compressive plastic strain CD and a compressive creep strain DA. In this example, the tensile plastic strain AB was reversed by a portion of the compressive plastic strain CD and likewise, the entire compressive creep strain DA was reversed by only a portion of the tensile creep strain BC. We therefore had a PP strainrange of magnitude AB, and a CC strainrange of magnitude DA. From the excess tensile creep strain and excess compressive plastic strain we have a CP strainrange of magnitude BC-DA. It should be noted that in any hysteresis loop, it is possible to have a maximum of only three of the four types of strainranges. It is not possible for the PC and CP type strainranges to be components of the same hysteresis loop. Procedures for partitioning complex hysteresis loops will be referred to in the section "Suggested Evaluation Program".

For the above, we have concluded that the inelastic strainrange, $\Delta\epsilon_{IN}$ = AC, is made up of the three components $\Delta\epsilon_{pp}$ = AB, $\Delta\epsilon_{cc}$ = DA, and $\Delta\epsilon_{cp}$ = (BC−DA). In equation form, $\Delta\epsilon_{IN} = \Delta\epsilon_{PP} + \Delta\epsilon_{cc} + \Delta\epsilon_{cP}$.

Let us now consider (with the aid of fig. 3) a numerical example with an inelastic strainrange AC of 0.0050, a tensile plastic strain AB equal to 0.0015, a tensile creep strain BC equal to 0.0035, a compressive plastic strain CD equal to 0.0030, and a compressive creep strain DA equal to 0.0020. The partitioned inelastic strainranges can now be determined from the following simple rules:

1) $\Delta\epsilon_{pp}$ is equal to the smaller of the plastic strains in the two directions. For the example, AB is 0.0015 and CD is 0.0030. Hence, $\Delta\epsilon_{pp}$ is 0.0015.

2) $\Delta\epsilon_{cc}$ is equal to the smaller of the creep strains in the two directions. For the example, BC is 0.0035 and DA is 0.0020. Hence, $\Delta\epsilon_{cc}$ is 0.0020.

3) $\Delta\epsilon_{cp}$ or $\Delta\epsilon_{pc}$ is equal to the remainder of the inelastic strainrange not assigned to $\Delta\epsilon_{pp}$ and $\Delta\epsilon_{cc}$. For the example, all but 0.0015 of the strainrange was assigned to $\Delta\epsilon_{PP}$ and $\Delta\epsilon_{CC}$.

Hence, 0.0015 is the remainder, and it is a $\Delta\epsilon_{cp}$ strainrange since the excess of creep of 0.0015 is in tension and the excess of plasticity of 0.0015 is in compression.

There remains the final task of predicting the cyclic life resulting from this combination of partitioned strainranges. We have proposed the Interaction Damage Rule (ref. 10) for this purpose. An example of how this rule is applied may be seen with the aid of figure 4. We must first have obtained the individual partitioned strainrange-life relationships as shown in figure 4. We must also have determined, as above, the magnitude of the individual partitioned strainranges for the particular hysteresis loop being analyzed. We then perform the following steps:

1) For the inelastic strainrange of interest - in this case $\Delta\epsilon_{IN}$ =AC, read off the values of cyclic lives N_{pp}, N_{cc}, and N_{cp}. It is not necessary to obtain a value of N_{pc} for this example since we have already determined that no such strainrange component exists in our example hysteresis loop (fig. 3).

2) Calculate the fractions for each of the partitioned strainranges as shown in figure 5. For this example, $F_{pp} = \Delta\epsilon_{pp}/\Delta\epsilon_{IN}$ = AB/AC, $F_{cc} = \Delta\epsilon_{cc}/\Delta\epsilon_{IN}$ = DA/AC, and $F_{cp} = \Delta\epsilon_{cp}/\Delta\epsilon_{IN}$ = (BC-DA)/AC. Note that $F_{pp} + F_{cc} + F_{cp} = 1$

3) The damage per cycle due to each of the components can be represented by F_{pp}/N_{pp}, F_{cc}/N_{cc}, and F_{cp}/N_{cp}. The total damage per cycle is $1/N_{PRED}$ and is equal to the sum of the individual damage contributions. Hence,

$$1/N_{PRED} = F_{PP}/N_{PP} + F_{CC}/N_{CC} + F_{CP}/N_{CP}$$

4) The predicted life N_{PRED}, for the hysteresis loop in question is then calculated using the above equation.

It is this total process of generating the individual failure life relationships, partitioning a hysteresis loop into its component strainranges, and combining the effects of these components to determine life, that we have called The Method of Strainrange Partitioning. The steps in this total process are what we are proposing to be examined by means of this cooperative evaluation program.

POTENTIAL UTILITY OF THE METHOD OF STRAINRANGE PARTITIONING

Characterizing Material Behavior

To date, we have been able to characterize several materials by the four independent partitioned strainrange-life relationships. Examples for six materials are shown in figure 5. In all cases, each relationship can be described adequately by a power law, i.e., linear plots of strainrange versus life on log-log coordinates. It should be noted that the ordering of these partitioned strainrange-life relationships is not the same for all the materials shown. For example, in some cases the CP, and in others the PC type strainrange is the most damaging. Verification of the power law relationships will be of great practical value in that it will minimize the amount of data required by future investigators to characterize any one of the lines. In most cases, we have found that 5 or 6 tests are required to adequately define any one of the lines.

A survey of the literature dealing with high-temperature fatigue shows one of the other major advantages of the proposed approach. In the past, it took a great variety of test types to completely characterize a material. Besides test temperature (which we shall deal with separately in a later section), specific design curves were necessary to account for a variety of testing frequencies, applied wave shapes, as well as for tensile and compressive hold times. All of these requirements made it almost impossible to completely charaterize a material so that the design data would be easily and generally applicable to all problems. It was therefore usually left to an investigator to match his own specific test program to his own application. The Strainrange Partitioning Method, which involves only the four partitioned strainrange-life relationships to characterize material behavior, should eliminate this dilemma that designers currently face.

Designers will still have to determine the type and magnitude of the strain being applied to their structure, but the failure curves, as represented by the partitioned strainrange-life relationships, are general in nature and can be applied to any specific situation. This should reduce the number and kinds of tests previously required by designers for the purpose of life prediction.

Figure 6 was prepared to demonstrate the ability of the approach to characterize material behavior. Tests were conducted on 12 alloys and the observed cyclic lives are in agreement with the calculated lives within factors of two. These tests were run at various frequencies and in many instances with tensile or compressive hold times under either constant stress or strain conditions. These results demonstrate, we believe, the ability of the Method of Strainrange Partitioning to characterize these materials for high-temperature, low-cycle fatigue.

Establishing Bounds on Life

Early in the design process, it is likely that the inelastic strains at critical locations in a structure will be known with at least a limited degree of accuracy. The Method of Strainrange Partitioning allows us to take advantage of this preliminary information and determine the expected upper and lower bounds on life without having to perform the partitioning of the hysteresis loops.

As can be seen from figure 4, if the inelastic strainrange, $\Delta\epsilon_{IN}$, were entirely of the PP type, the most the life could possibly be is N_{PP}. On the other hand, for this illustrative example, if $\Delta\epsilon_{IN}$ were made up entirely of the most damaging type of strainrange (CP in this illustrative case), the life could be no less than N_{CP}. In other words, the upper and lower bounds on life for any given inelastic strainrange can be obtained from the assumption that the actual life must lie between the most conservative and least conservative of the partitioned strainrange-life relationships.

These bounds on life can be further narrowed if one wishes to make some additional assumptions regarding the types of strainrange components that can exist in the structure being analyzed. For example, for certain thermal fatigue problems, the designer might know that the CP type of cycle is not possible in the critical location being analyzed. This type of information might eliminate the CP failure mode from consideration and thereby alter the lower bound on life from N_{CP} to N_{CC}.

We now know that two or more of the four partitioned strainrange -life relationships can be quite close to each other for some materials. This could result in upper and lower bounds that are also quite close. In such a case, any further refinement of the calculations required to more accurately determine the types of strainranges present, might not be justified. This could greatly reduce the effort required for life prediction without any appreciable sacrifice in accuracy.

Relative Insensitivity to Temperature

Experience indicates that low-cycle fatigue life may be sensitive to test temperature. In general, the higher the temperature, the lower the life. This trend can be rationalized by recognizing that the effect of temperature can be two-fold; its effect on the flow behavior and on failure behavior. It is well known that the flow behavior of materials is highly temperature sensitive. The higher the temperature, the greater the likelihood for creep deformation rather than plasticity. The failure behavior, which is represented by the life relationships, on the other hand, is not so sensitive to temperature. We have investigated (ref. 11) the influence of temperature on the failure relationships for two alloys, 316 stainless steel and 2 1/4 Cr-1Mo steel. A summary of these results is shown in figure 7 where it can be seen that temperature has a negligible effect on the failure relationships. Reasons for the behavior were documented in reference 11. Hence, the role of temperature in influencing fatigue life for these two alloys is to alter the partitioning of creep and plasticity in a cycle, but not to alter the failure relationships. The latter insensitivity is an important aspect that can enhance the utility of Strainrange Partitioning. Fewer tests are required to characterize the high temperature fatigue behavior, and the analysis of cycles involving changing temperatures is greatly simplified.

Application to Complex Loading Cycles

We have to date, obtained only limited data indicating that the Method of Strainrange Partitioning works well for predicting lives for complex cycles. We used the partitioned strainrange-life relationships for 316 stainless steel generated at 705C to predict lives for tests in which the temperature was cycled both in-phase and out-of-phase with the applied strain. The results of these predictions are shown in figure 8.

For the in-phase tests, the minimum applied strain occurred at the minimum test temperature (230C) and both the strain and temperature were increased at a constant rate until the peak strain was reached at the same time the peak temperature was reached (750C). The strain and temperature were cycled in this manner until failure occurred. For the out-of-phase tests, the temperature cycle was reversed so that the minimum strain occurred with the maximum temperature and the maximum strain with the minimum temperature.

Since almost all the creep strain was introduced into the hysteresis loop near the peak temperature, the in-phase cycle was a combination of PP and CP type strain while the out-of-phase cycle was a combination of PP and PC type strain. Predicted lives for these tests (fig. 8) fell within the same factors of two of the observed lives as did the isothermal test results shown in figure 7.

SUGGESTED EVALUATION PROGRAM

It should be borne in mind that a reasonably well equiped high-temperature, low-cycle fatigue laboratory is needed by any organization contemplating participation in the suggested evaluation program. In suggesting the program outlined in Table I, for evaluating Strainrange Partitioning, we considered a number of possible alternatives, but finally decided that the best interests of all concerned would be served if each participating organization were to choose a material that is of greatest interest to themselves. One laboratory might select a material to evaluate because they have already characterized it with respect to other properties, or they might choose a material that is new to them but one for which they must determine properties for some future application. For whatever reasons, the material choice should be in the hands of each participant. In this way, each organization would be generating information of value to themselves. Everyone else would benefit from the fact that the characteristics of a number of different alloys would be determined and hence a broader-based evaluation of Strainrange Partitioning could be achieved.

Having selected a material to evaluate, it is suggested that four important aspects of Strainrange Partitioning be investigated. These will be discussed in detail in the ensuing text and are as follows:

1. Determine the basic life relationships for the PP, CC, PC, and CP type strainranges.

2. Demonstrate the transition in life between two bounding curves as a result of systematically changing one of the testing parameters such as cyclic straining rate.

3. Determine the effect of test temperature on the life relationships established above.

4. Analyze tests with complex or "mixed" cycling conditions by partitioning strains, computing damage components, and predicting lives.

The proposed testing and evaluation program, if conducted in its entirety, would require approximately two years and 50 high-temperature, low-cycle fatigue tests. However, only about 25 tests would be required to accomplish a minimum program. It would also be desireable to conduct a few standard tensile and creep-rupture tests on each alloy involved in the program to document its more conventional properties.

It is suggested that a baseline elevated temperature be selected for conducting the majority of the tests. This temperature should be high enough that creep effects can be readily introduced within reasonable times. For example, a testing temperature of 650C would be a good choice for stainless steels, whereas 900C would be more appropriate for an advanced nickel-base superalloy. Baseline test temperatures should be chosen such that some tests could be conducted at temperatures of 100C above and below the baseline temperature and still be able to introduce creep effects in a practical time span.

Ability to Characterize Material Behavior

The four basic partitioned strainrange-life relationships shown schematically in figure 9, can be determined by conducting isothermal laboratory tests that feature the individual strainranges of interest. Six test points are suggested for determining each of the curves. Examples of tests that feature the four components will now be presented.

<u>PP type tests-</u> This test consists of only plastic strain in both the tensile and the compressive halves of the cycle. No creep strain is permitted. The hysteresis loop for a PP type cycle is shown in figure 10a. To achieve this condition at high temperatures, it is necessary to cycle the strain at a frequency sufficiently high so as to preclude the introduction of time-dependent creep strain. Continuous strain cycling tests at frequencies on the order of 0.5 to 2.0 Hz have been used in previous research (ref. 9) and have been found to be acceptable. The minimum frequency required to exclude creep effects can be determined experimentally by conducting a series of tests at progressively higher and higher frequencies until a plateau in stress-strain response or in cyclic life is reached. All PP type tests would then be conducted at or above this minimum frequency.

The programmed strain-time wave-shape should be either a sine-wave or a triangular wave, with a preference for the latter. Strainranges for the six PP type tests should be selected so as to give lives covering the range between approximately 50 to 50,000 cycles to failure. A plot such as is indicated schematically in figure 9, can then be constructed of $\Delta\epsilon_{PP}$ versus the number of cycles to failure, N_{PP}, on logarithmic axes. It is necessary that this relationship be established prior to the evaluation of the other three life relationships.

CP type tests- There are a number of testing techniques that can be used to achieve a cycle that features the CP strainrange. Of the three most common cycles, there is a preference for the one involving a constant tensile creep stress as shown in Fig. 10b. This cycle is the most efficient in terms of obtaining the greatest amount of creep strain in the least amount of testing time. Furthermore, the magnitude of the creep strain is readily identifiable. We have conducted numerous tests of this type at NASA-Lewis and have found the technique to work well. The test can be executed under servo load control with external strain limits superimposed. A tensile creep stress is programmed to act for as long as is necessary to produce a predetermined amount of tensile strain. When this tensile strain limit is reached, the servo-controller calls for a compressive stress that is somewhat greater than the capacity of the material. To prevent the compressive loading from occuring too rapidly and from producing large compressive strains, we have purposely throttled down the oil supply to the hydraulic actuator with a small orifice needle valve. The compressive deformation rate is thereby controlled at a rate that has been previously determined to be high enough to preclude creep effects but not so high as to cause overshooting of the compressive strain limit (equal in magnitude to the tensile strain limit). When this limit is reached, the servo-controller calls for the previously applied tensile stress, and the cycle proceeds and repeats itself until failure occurs.

The value of the tensile stress to be used in such cycles must be low enough that the creep strain is the dominant strain in the tensile portion of the cycle, yet large enough that the creep time per cycle is not prohibitively large. Should a material undergo significant cyclic hardening or softening, the time duration of the creep portion of the cycle can change drastically unless the creep stress level is periodically and appropriately increased or decreased. Since the important aspect of these tests is to impose and measure an amount of creep strain, there should be little concern for the magnitude of the stress responsible for producing this strain. This is analogous to permitting, and essentially ignoring, the stress level changes that are associated with cyclic hardening or softening during high frequency cycling to establish the PP type behavior.

When the desired inelastic strainranges are too small for practical application of the cycles discussed above, the tensile strain, hold-time cycle (fig. 10c) is preferred. Here, the straining is done in exactly the same way as for the PP type cycle <u>except</u> that a hold period is introduced at the peak tensile strain. During the hold period, stress relaxation occurs by a creep mechanism. The amount of creep strain incurred per cycle is equal to the amount of elastic strain that is relaxed. Only a small amount of creep strain can be obtained in this fashion, and since it is always desireable to feature the type of strainrange of interest, this test cycle should only be used when the desired inelastic strainrange is small. The magnitude of the tensile creep strain per cycle is equal to the CP strainrange and the balance of the inelastic strainrange in the cycle must therefore be equal to the PP strainrange.

A third testing technique that features the CP strainrange is a strain cycle that involves a very low straining rate during tensile deformation, but a very high straining rate during the compressive deformation portion of the cycle (fig. 10d). Although this type of cycle is a relatively simple one to employ, the interpretation of the results is not as straight-forward as for the other two techniques just discussed. The major problem is in the interpretation of how much of the tensile strain is creep strain, and how much is plastic strain. Since the stress and strain response are not of a form from which the creep strain can be readily identified, the tensile strain would have to be partitioned into its component strains by some independent means. Although procedures have been proposed for performing such partitioning, they are not as positive an identification of the relative portions of creep and plastic strains as can be obtained by employing the other two testing techniques. This cycling technique is recommended only if the other two types of cycles cannot be achieved with testing equipment currently available within the participating organizations' laboratories.

Before the $\Delta\epsilon_{cp}$-N_{cp} relationship can be plotted, the damage due to the presence of any PP type strainrange must be accounted for. Hence, it is necessary that the $\Delta\epsilon_{pp}$-N_{pp} relationship be known at this stage in the evaluation program. In this case, only PP and CP strainrange components are present, and the fractions, F_{pp} and F_{cp} are known. The Interaction Damage Rule shown in figure 4 can now be used in a reverse procedure. The experimentally observed life is substituted for the predicted life, and the equation is solved for the unknown value of N_{cp}. This N_{cp} life represents the life that would have been obtained had there been no contribution from PP type damage. Hence, the inelastic strainrange of the cycle is plotted against this N_{cp} life value. These results can then be plotted as shown in figure 9. Strainranges for the six CP type tests should cover approximately the same regime as was used to establish the $\Delta\epsilon_{pp}$-N_{pp} relationship.

PC type tests- Tests appropriate for the determination of the life relationship are almost identical to the CP tests. The only difference between the two is in the direction of the creep portion of the cycle as seen from a comparison of the CP and PC cycles in figures 10b through 10g. Hence, by interchanging the tensile and compressive notations in the previous section, the testing and evaluation techniques for PC type straining can be obtained.

CC type tests- There are also three basic testing procedures for generating strain cycles with completely reversed creep strains, i.e., CC type strainranges. In fact, such cycles are, in principle, formed by using just the tensile portion from the CP test and the compressive portion from the PC test. The preferred cycle (fig. 10h) involves the use of the cyclic creep rupture test (ref. 12) wherein a constant tensile stress is servo-controlled until a preset tensile strain limit is reached by creep. When the limit is reached, the direction of the stress is rapidly reversed and an equal valued constant compressive stress is servo-controlled until a preset compressive strain limit is reached. Upon reaching this limit, the tensile stress is reapplied and the test is continued in the above fashion until failure occurs. Again, it may be necessary to periodically increase or decrease the magnitude of the creep stresses as the test progresses in order to maintain a desired creep strainrange or time per cycle. Our experience has been that under CC type straining conditions, creep rates increase throughout the test when the stress amplitude is held constant.

There will always be a PP component of strainrange in the above type of test. Furthermore, there may also be an unbalanced component of strainrange such as CP or PC depending upon whether the unbalance of creep strain is in the tensile or compressive half of the cycle. Before the undesirable damaging effects due to the presence of any PP, and CP or PC type strainrange can be factored out of the test results, it is necessary to have conducted the PP, CP, and PC type tests and to have already established these three life relationships.

When the desired inelastic strainrange is small, the above type of cycle may be difficult to control. In that event, an alternative type test (fig. 10i) is a rapid strain cycling test with hold periods superimposed at both the peak tensile and compressive strains. During these peak strain hold periods, the stresses relax and elastic strain is in effect converted into creep strain. If the amount of stress relaxation is the same in both tension and compression, there is no component of unbalanced strainrange present in the cycle. Hence, the CC strainrange is equal to the amount of creep strain relaxed during either the tensile or compressive halves of the cycle. The balance of the inelastic strainrange is equal to the PP strainrange.

The third means of producing balanced creep strain in a cycle (fig. 10j) is to simply perform a completely reversed strain cycle at a low enough frequency that creep can occur. As discussed earlier with respect to CP type testing, this procedure introduces another difficulty since creep strain that is incurred is not readily identifiable. Hence, a supplementary partitioning test would be required to partition the inelastic strainrange into its CC and PP components. An unbalanced strainrange component (PC or CP) would not be expected in this type of test provided the straining rates in tension and compression were equal.

General comments- Each participating laboratory should select the testing techniques that are best suited to their capabilities. However, in selecting techniques, it must be understood that there are some practical limitations that must be taken into consideration. For example, when a CC type test is being conducted to establish the $\Delta\epsilon_{cc}-N_{cc}$ relationship, it is imperative that the dominant damage in the cycle be due to the CC type strainrange component. In reference 9, we suggested using a criterion that at least one half of the damage done in a test with an observed life N_{OBS} (e.g., $F_{cc} \times N_{OBS} / N_{cc} > 0.5$ for a CC cycle), must be due to the strainrange component of interest. Only if this criterion is met can a test point be used in the establishment of the life relationship.

We have since found from experience, that it is also desireable to impose still another restriction on whether or not a test point should be used in the establishment of one of the basic life relationships. Although not a mandatory requirement, the strainrange component of interest should be the dominant component, that is, the strainrange fraction F, should be at least one half.

Ability to Establish Bounds on Life

Having once determined the four partitioned strainrange-life relationships in accordance with the tests described in the previous section, the premise that Strainrange Partitioning can be used to represent bounds on cyclic life can now be evaluated.

Ideally, no cycle will produce lives greater than indicated by the PP line, and lives can not be achieved that are lower than indicated by the three curves involving creep strain in the three different extreme modes. A balanced strain cycle, for example, would have its lowest life bounded by N_{cc} and the highest life by N_{pp}. Or, considering an unbalanced cycle wherein only tensile creep is involved, the lowest possible life would be N_{cp} and the highest possible life would be N_{pp}. As a check on this premise of Strainrange Partitioning, we would suggest a limited evaluation in which approximately six specimens would be subjected to a series of tests in which a single controlled variable (such as frequency, hold time, tensile creep stress, or whatever variable is convenient) is systematically changed from one test to the next. The simplest example would be to select a balanced strain cycle and at a given test temperature and strainrange, vary the test frequency. At the highest frequency, the strainrange would be all PP, and as frequency is decreased, CC type strain would gradually displace the PP type strain, and the cyclic life would drop from a maximum of N_{pp} to a minimum of N_{cc}. The results might take on the appearance as indicated schematically in figure 11.

Degree of Temperature Insensitivity

A potentially beneficial aspect of characterizing the high-temperature low-cycle fatigue behavior of materials in terms of the four partitioned strainrange-life relationships is that for a number of materials, these life relationships should not be expected to vary appreciably as the testing temperature is either increased or decreased. Although temperature has a profound influence on constitutive relationships (i.e., flow behavior, or stress-strain-time response), the influence of temperature on the cyclic fracture process is not particularly a strong one. In fact, it can be neglected for many engineering materials. To evaluate this aspect of Strainrange Partitioning, the following program is suggested.

For each of the life relationships already determined, additional tests could be conducted featuring each of the four basic strainranges. For each of the four basic type cycles, a minimum of two tests could be conducted at temperatures of 50 and 100 Centigrade degrees above and below the baseline temperature used in generating the basic life relationships. The ensuing test results would be used to establish new points for direct comparison with the original life relationships. A suggested method of comparison of these new test results with the baseline results is indicated in figure 12.

Ability to Predict Behavior For Complex Cycles

Another advantageous aspect of Strainrange Partitioning is its inherent ability to handle any generalized strain cycle (for example, fig. 13a) regardless of its complexity. Any inelastic strain can be separated into time-dependent and time-independent components. We have proposed both analytical (see reply to Husslage's and Krempl's discussions of ref. 13) and experimental techniques (refs. 10, 13, and 14) for partitioning strains within a "mixed" cycle, i.e., a cycle with combinations of PP, CP or PC, and CC type strainranges.

Once partitioned, and once the life relationships have been determined as in figure 13b, the process of predicting the life N_{PRED}, associated with a mixed cycle is reduced to a simple algebraic exercise of solving the following expression.

$$F_{PP}/N_{PP} + F_{CC}/N_{CC} + F_{CP}/N_{CP} + F_{PC}/N_{PC} = 1/N_{PRED}$$

As a demonstration of the potential of Strainrange Partitioning in predicting cyclic lives of mixed cycles, it is suggested that a few strain cycling tests with some complicated wave shape or pattern be performed, the inelastic strains partitioned into creep and plastic components, and the cyclic lives predicted and compared with experimentally observed lives. The choice of cycles is left entirely to the participant, since the equipment available within his laboratory will dictate the degree of complexity of the cycle. Approximately six test specimens could be devoted to such an evaluation, and the results should be displayed as shown schematically in figure 13c.

Coordinating Responsibilities

The proposed program would require coordination of some phases of the effort. It is suggested that AGARD appoint a Program Coordinator who could act as a clearing house for accumulating and disseminating mutually beneficial information. For example, the participating laboratories should be made aware of each other's choice of material and test conditions to avoid unnecessary duplications. The extent of progress should also be monitored so that adequate time is permitted to plan for a symposium at which time the results could be presented to all concerned.

CONCLUDING REMARKS

The Strainrange Partitioning approach to high-temperature low-cycle fatigue has been undergoing continuous development at the NASA-Lewis Reseach Center since its introduction in 1971. The concept has been developed to the point where we are confident of the fundamental soundness of the method and enthusiastic about the promise the approach holds for materials specialists and designers who are in a position to take advantage of its many attributes.

We feel, therefore, that the time is right for this cooperative evaluation program which has the objective of achieving the goal of broader evaluation and verification through the additional experience that can be provided by the outstanding laboratories and personnel that would participate. It is through this type of cooperative effort that we hope to accelerate the often time consuming process of developing new and promising ideas and bringing them to the point of acceptance and use.

We recognize that participation in this evaluation program will in itself not accomplish the set goal. It is also necessary to jointly assess the results of this program if strengths and weaknesses are to be identified and a progressive course of action formulated. We therefore suggest that AGARD appoint a Program Coordinator and that a symposium be planned tentatively for two years hence, in which all the participating laboratories present their findings and discuss a future course of action.

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TABLE I

SUGGESTED PROGRAM

STEP 1	SELECT ALLOY OF INTEREST
STEP 2	SELECT ONE TEST TEMPERATURE OF INTEREST
STEP 3	ESTABLISH PP STRAINRANGE-LIFE RELATION
STEP 4	ESTABLISH CP & PC STRAINRANGE-LIFE RELATIONS
STEP 5	ESTABLISH CC STRAINRANGE-LIFE RELATION
STEP 6	ESTABLISH VALIDITY OF ORIGINAL STRAINRANGE-LIFE RELATIONS FOR PREDICTING UPPER & LOWER LIFE BOUNDS
STEP 7	ESTABLISH VALIDITY OF ORIGINAL STRAINRANGE-LIFE RELATIONS FOR PREDICTING LIFE AT OTHER TEMPERATURES
STEP 8	SELECT A "MIXED" CYCLE, PARTITION IT, PREDICT LIFE

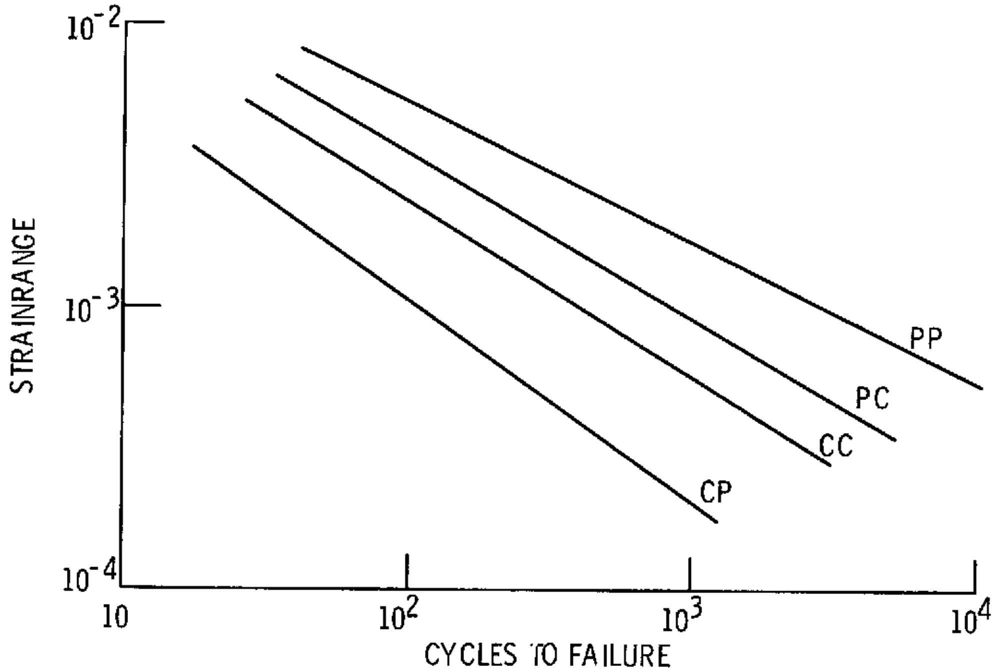

Figure 1. - Typical partitioned strainrange-life relationships used to characterize material behavior in the creep-fatigue range.

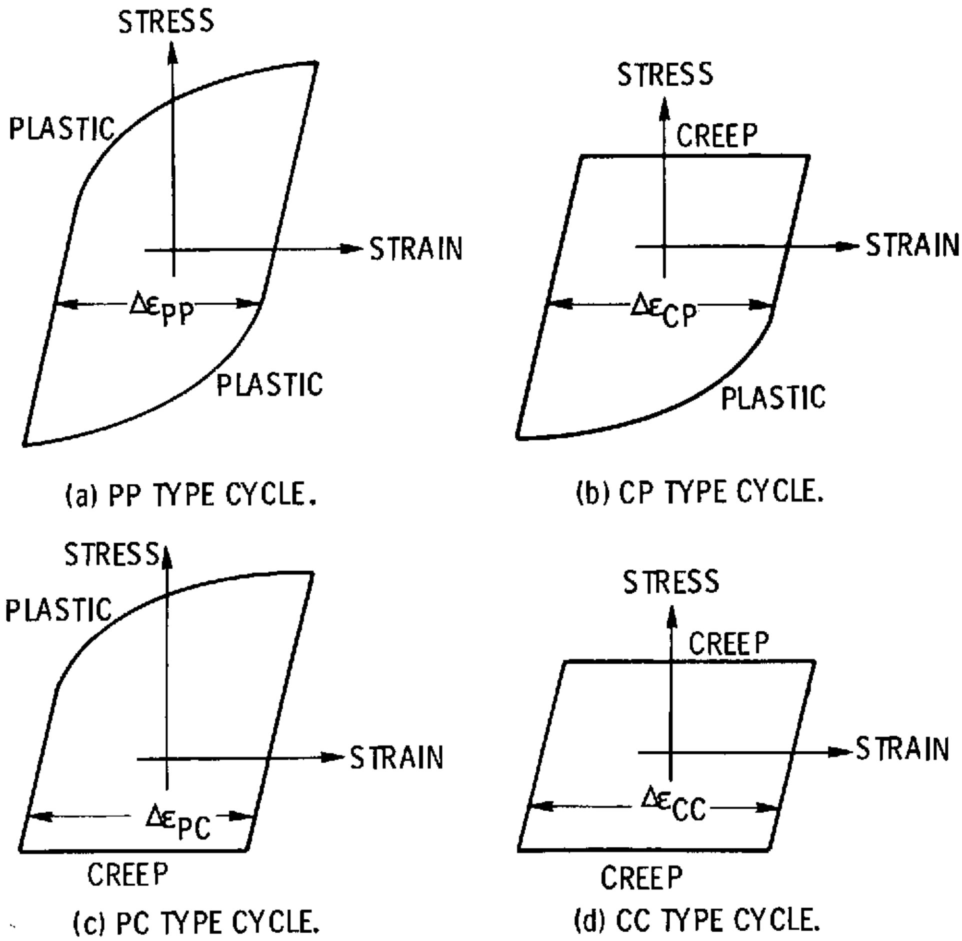

Figure 2. - Idealized hysteresis loops used in defining the individual partitioned strainrange-life relationships.

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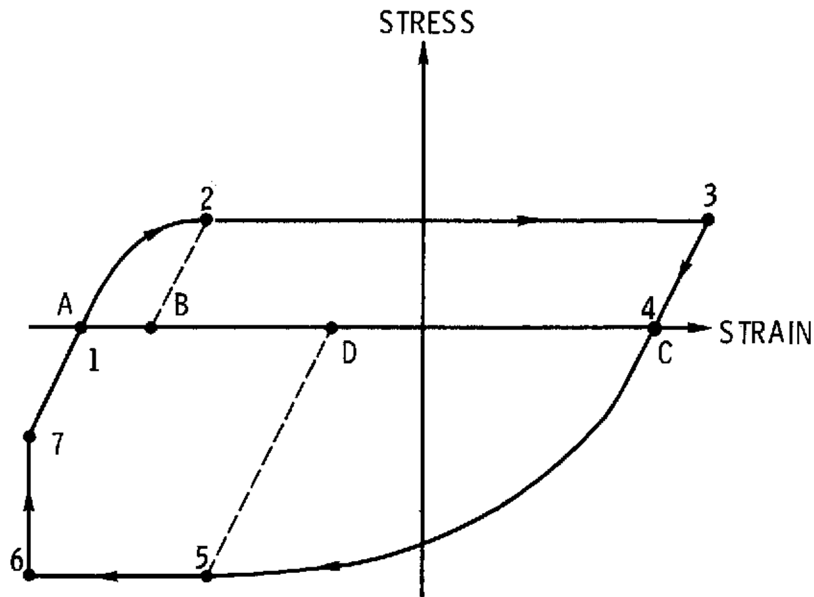
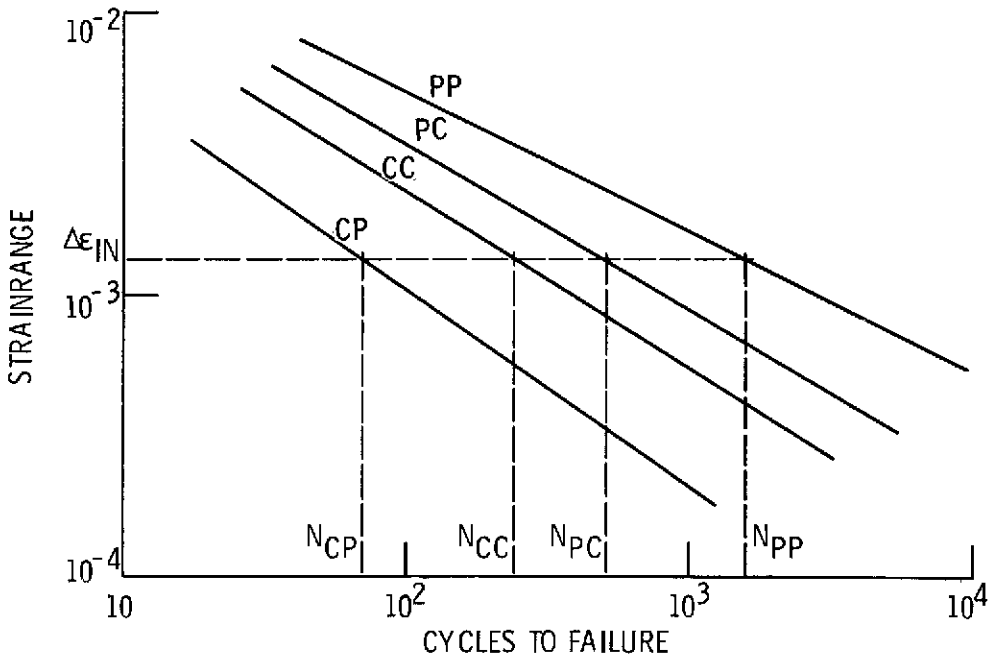


$$\Delta\varepsilon_{PP} = AB \qquad \Delta\varepsilon_{CC} = DA$$
$$\Delta\varepsilon_{PC} = 0 \qquad \Delta\varepsilon_{CP} = (BC - DA)$$
$$\Delta\varepsilon_{IN} = \Delta\varepsilon_{PP} + \Delta\varepsilon_{CC} + \Delta\varepsilon_{CP} = AC$$

Figure 3. - Defining the partitioned strainrange components of a complex hysteresis loop.



$$F_{PP} = \Delta\varepsilon_{PP}/\Delta\varepsilon_{IN} \qquad F_{CC} = \Delta\varepsilon_{CC}/\Delta\varepsilon_{IN}$$
$$F_{PC} = \Delta\varepsilon_{PC}/\Delta\varepsilon_{IN} \qquad F_{CP} = \Delta\varepsilon_{CP}/\Delta\varepsilon_{IN}$$
$$1/N_{PRED} = F_{PP}/N_{PP} + F_{CC}/N_{CC} + F_{PC}/N_{PC} + F_{CP}/N_{CP}$$

Figure 4. - Definition of terms for the Interaction Damage Rule.

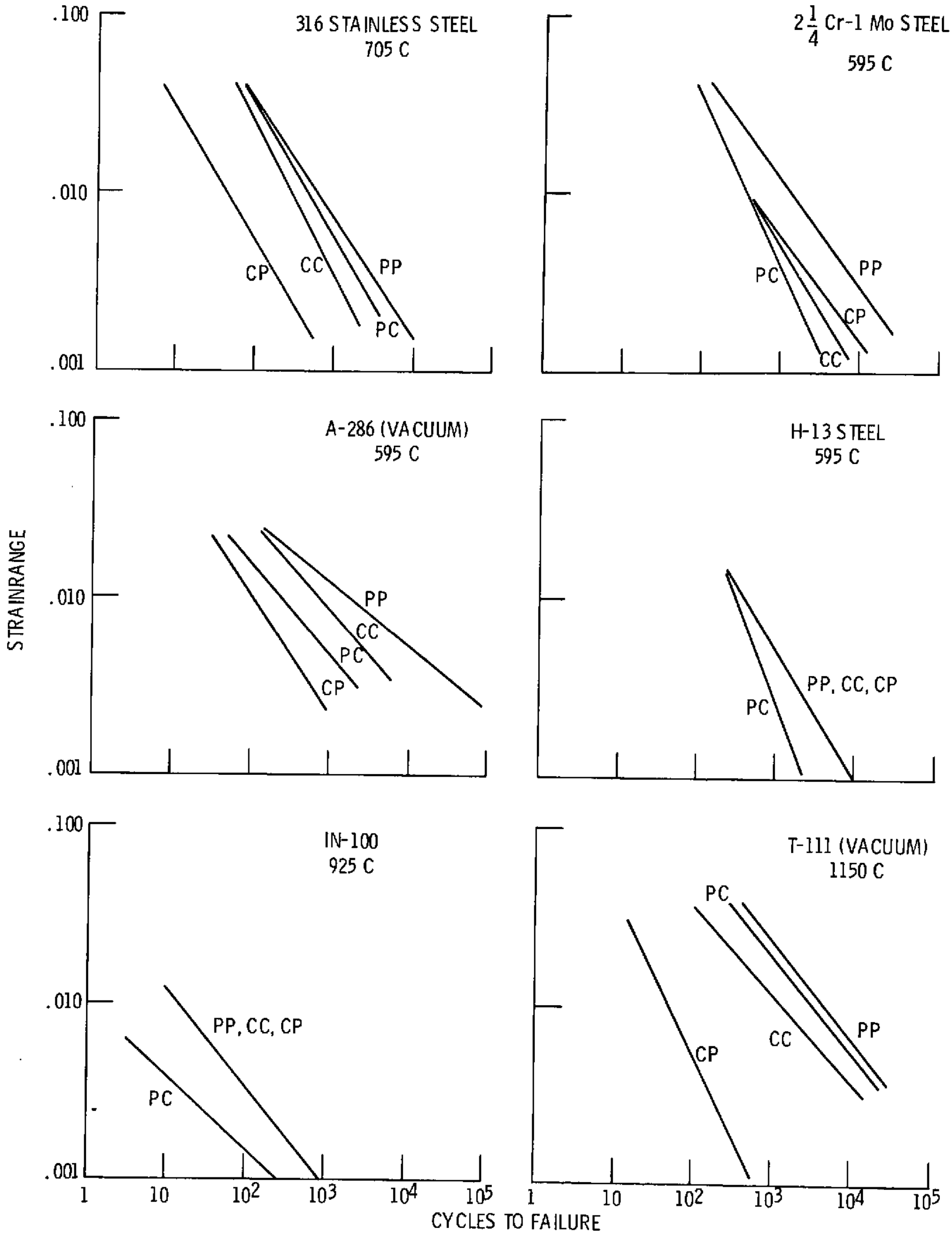


Figure 5 - Partitioned strainrange-life relationships for six alloys.

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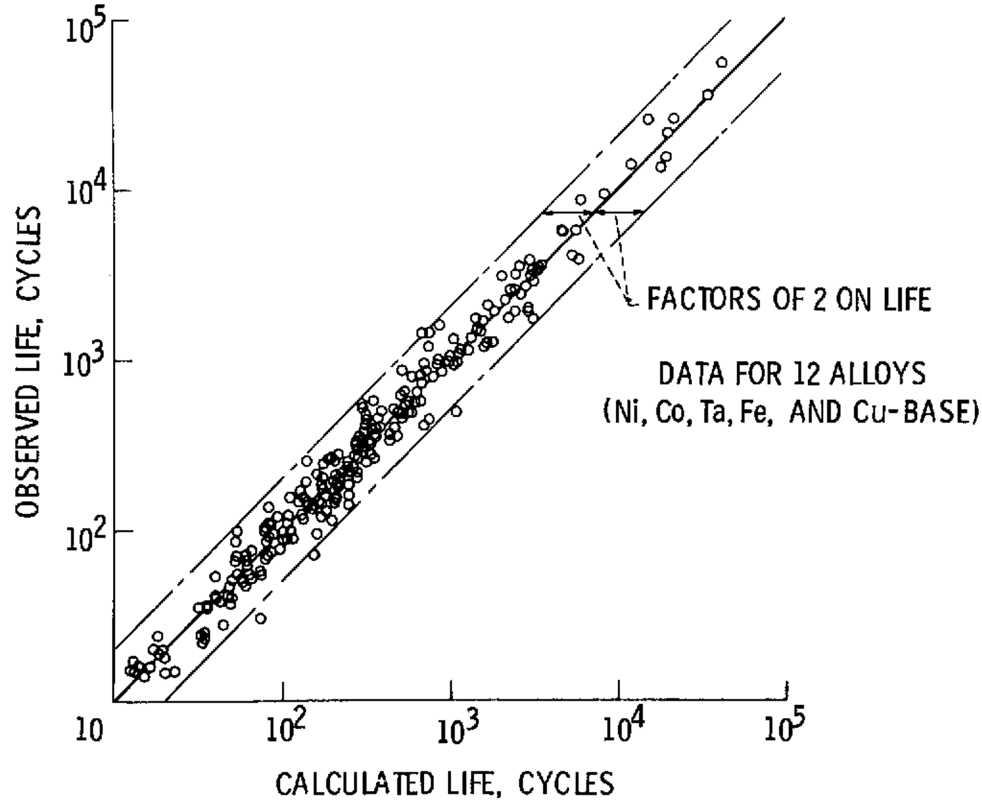

Figure 6. - Ability of Strainrange Partitioning to characterize material behavior in the creep-fatigue range.

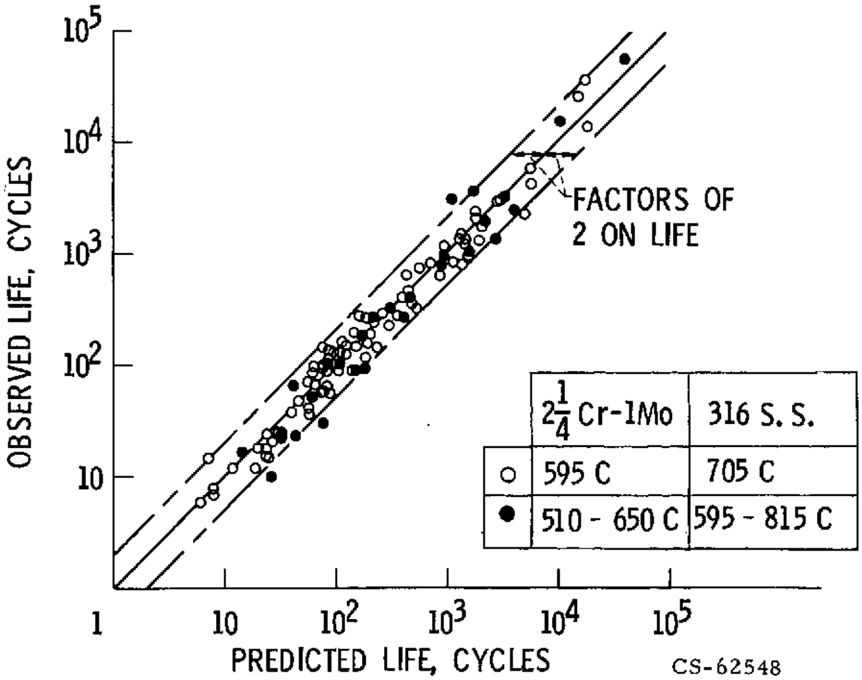

Figure 7. - Comparison of observed and predicted life at different temperatures using Strainrange Partitioning approach.

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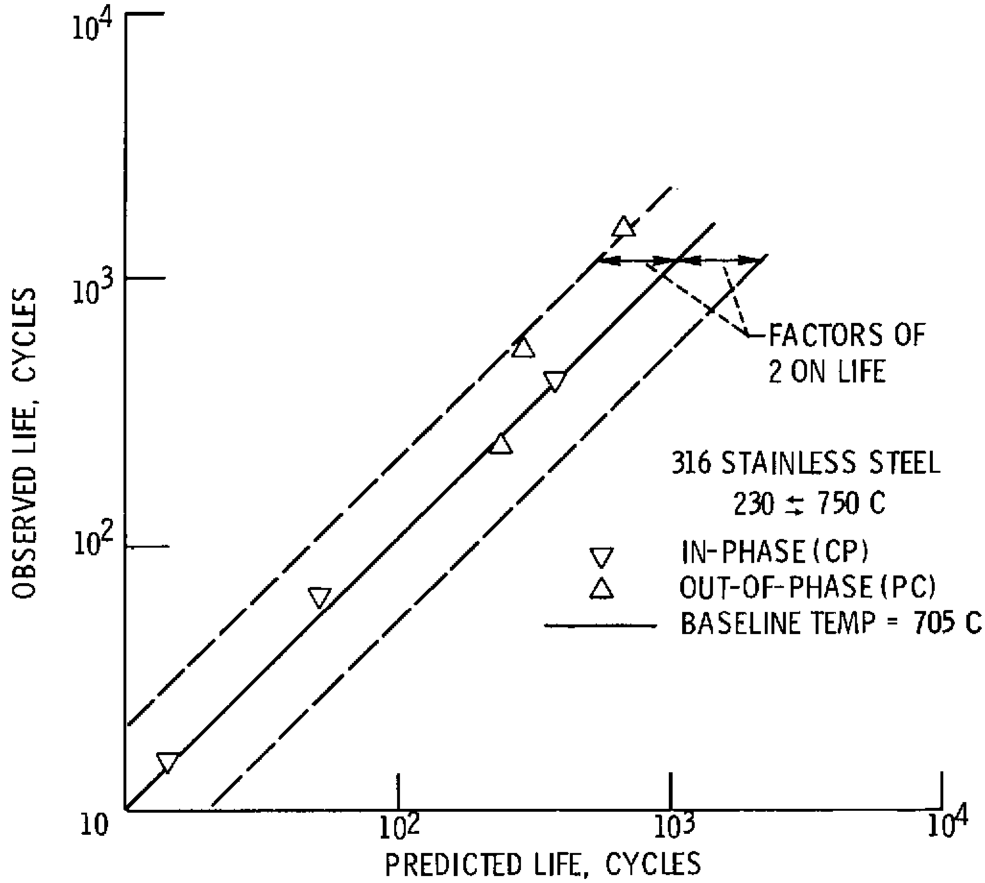

Figure 8. - Ability of Strainrange Partitioning to predict lives for in-phase and out-of-phase tests from isothermal data.

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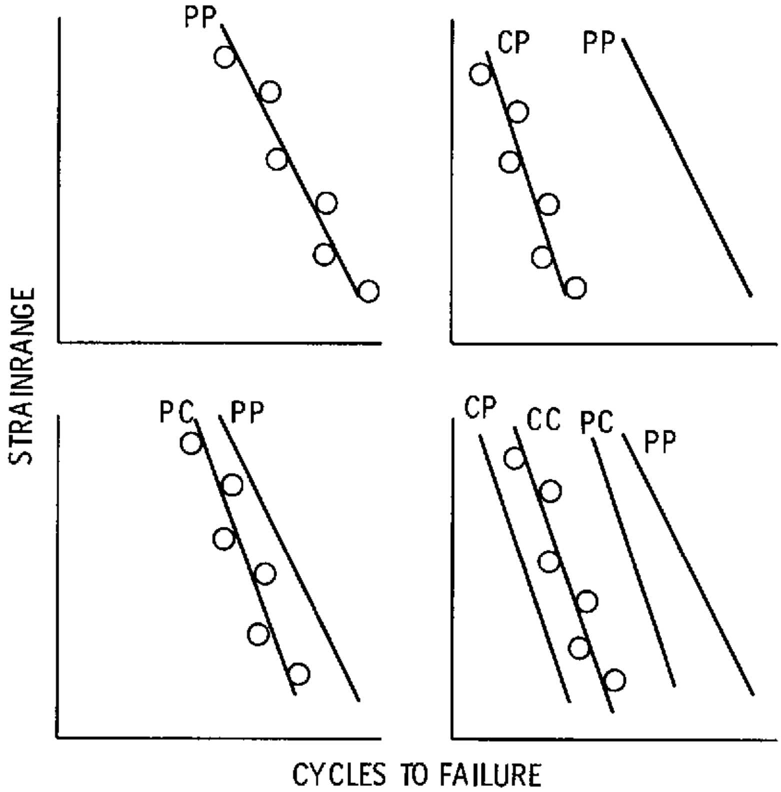

Figure 9. - Procedure for generating the isothermal partitioned strainrange-life relationships.

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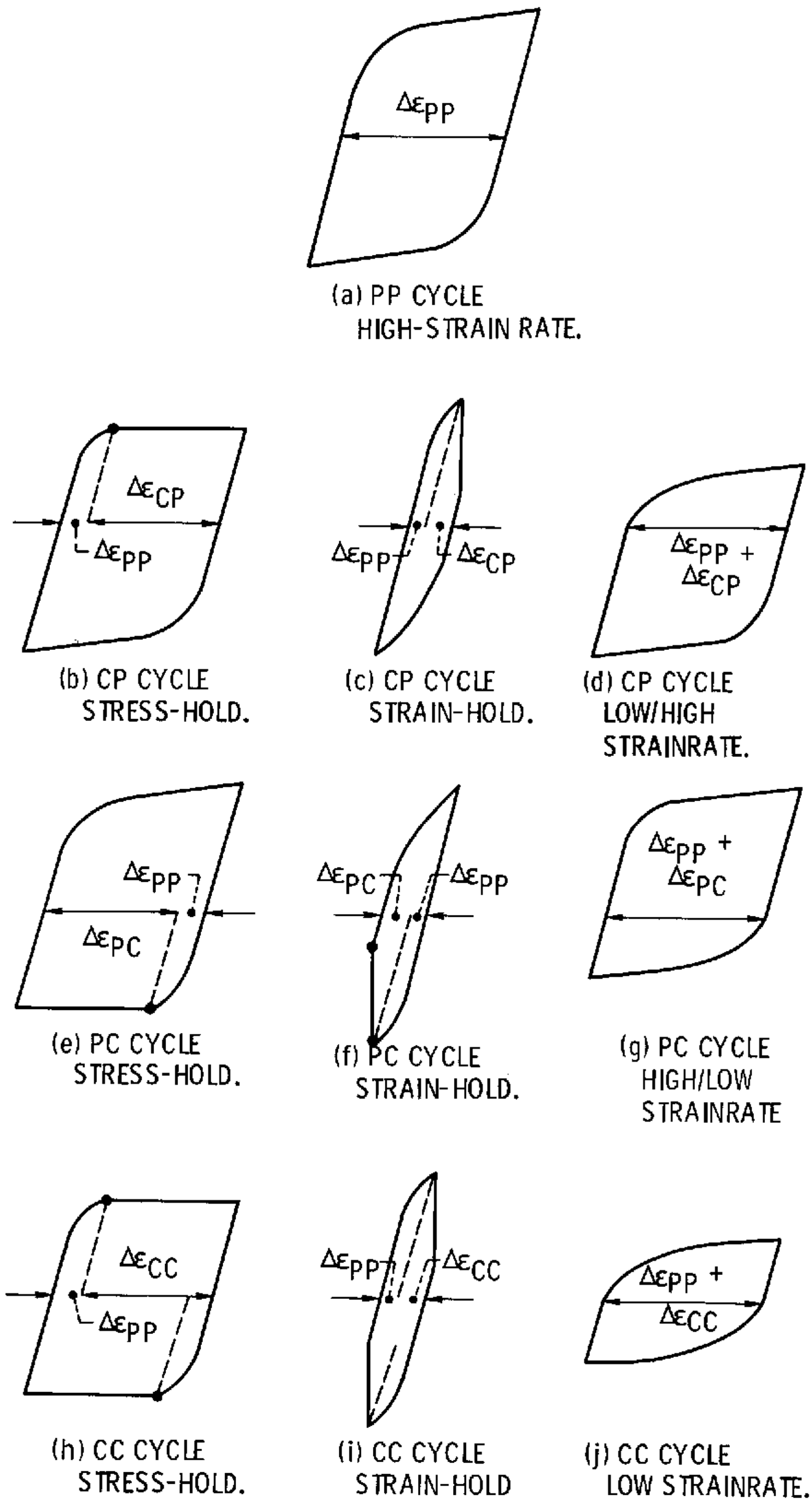

Figure 10. - Examples of isothermal test cycles to determine the partitioned strainrange-life relationships.

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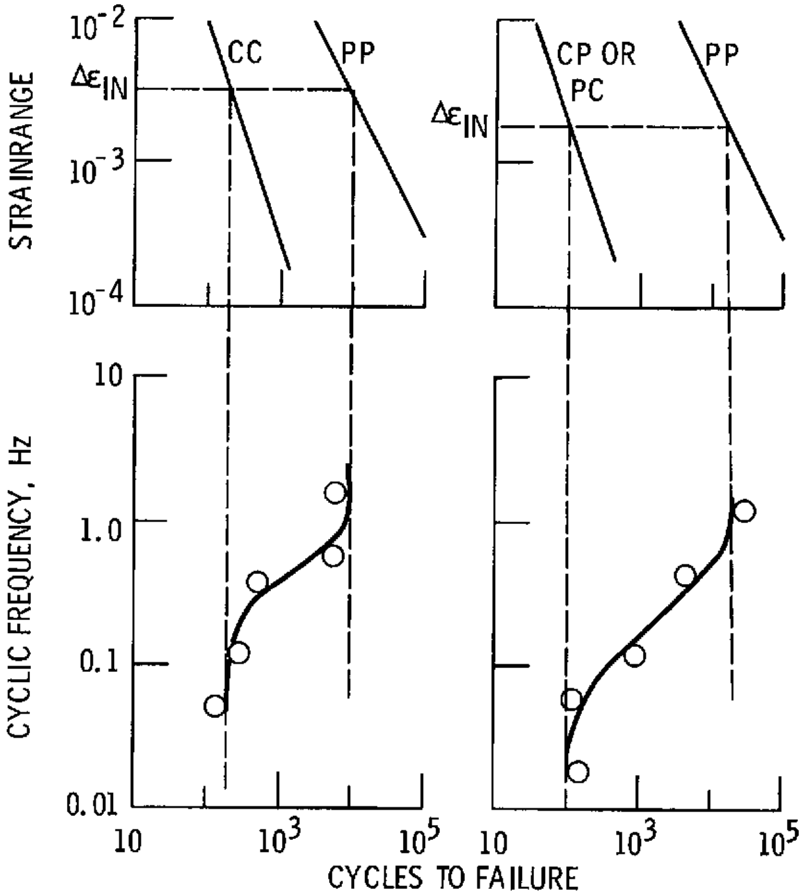

Figure 11. - Use of partitioned strainrange-life relationships to obtain bounds on life.

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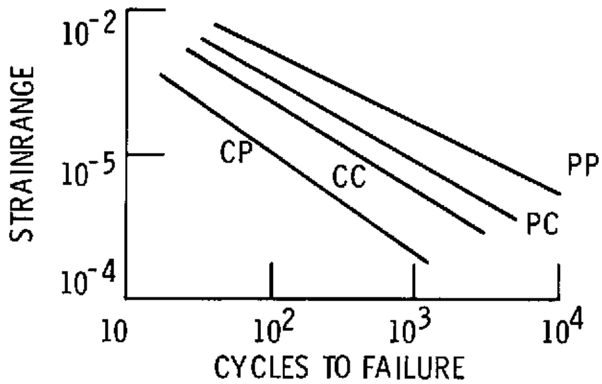
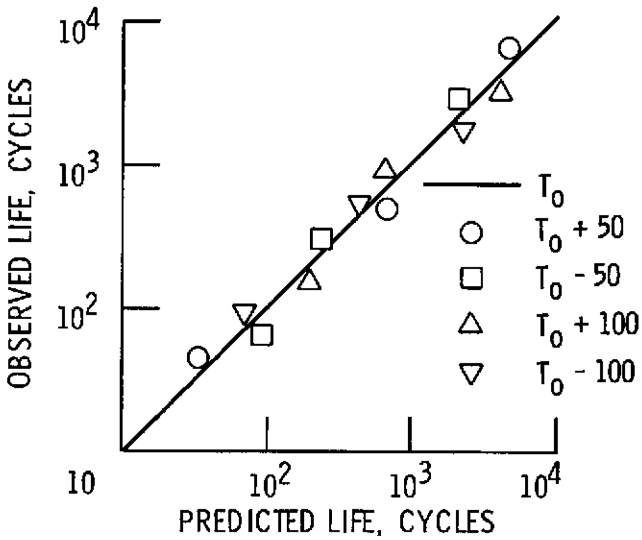


(a) GENERATE ISOTHERMAL PARTITIONED STRAINRANGE-LIFE RELATIONSHIPS AT TEMPERATURE T_0.



(b) PREDICT LIVES AT OTHER CYCLES.

Figure 12. - Use of partitioned strainrange-life relationships obtained at one temperature to predict behavior at other temperatures.

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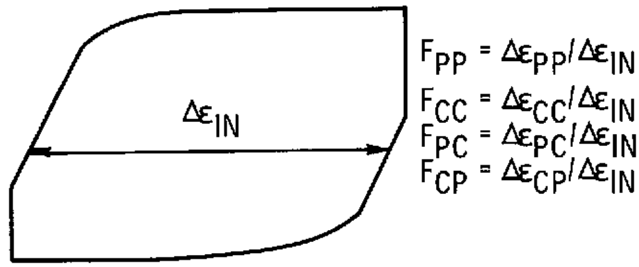
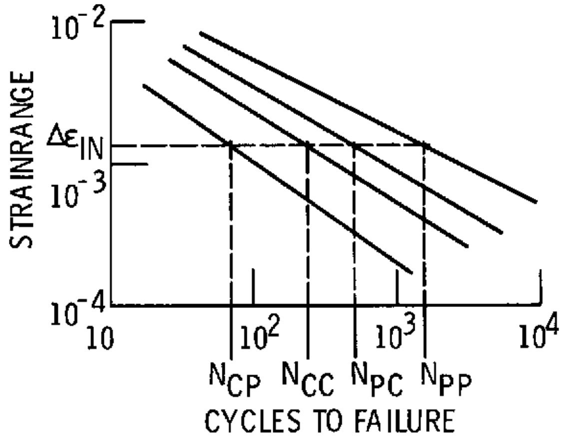
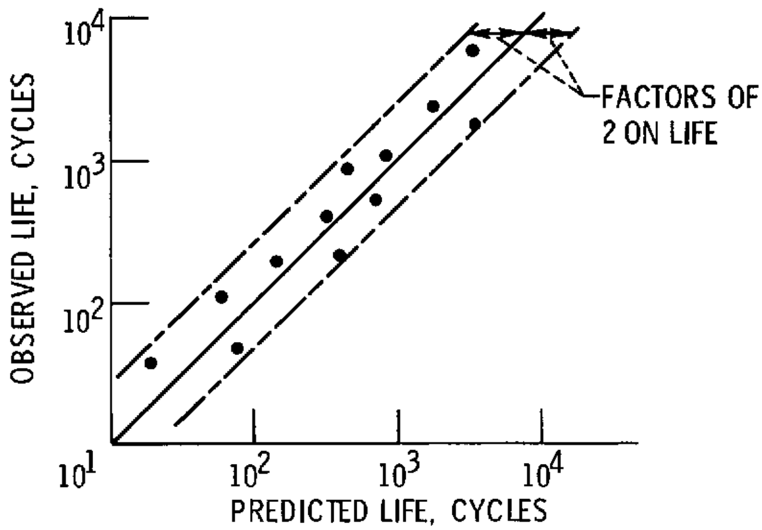


(a) DETERMINE $\Delta\varepsilon_{IN}$, F_{PP}, F_{CC}, F_{PC}, AND F_{CP}.



$$1/N_{PRED} = F_{PP}/N_{PP} + F_{CC}/N_{CC} + F_{PC}/N_{PC} + F_{CP}/N_{CP}$$

(b) PREDICTION OF LIFE.



(c) PLOT PREDICTED VS. OBSERVED LIVES

Figure 13. - Use of partitioned strainrange-life relationships and Interaction Damage Rule to predict lives for complex cycles.