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Abstract

Procedures based on Strainrange Partitioning (SRP) are presented for estimating the effects of environment and other influences on the high-temperature, low-cycle, creep-fatigue resistance of alloys. It is proposed that the plastic and creep ductilities determined from conventional tensile and creep-rupture tests conducted in the environment of interest be used in a set of ductility normalized equations for making a first order approximation of the four (SRP) inelastic strainrange-life relations. Different levels of sophistication in the application of the procedures are presented by means of illustrative examples with several high temperature alloys. Predictions of cyclic lives generally agree with observed lives within factors of three.

Introduction

In keeping with the theme of this conference on Environmental Degradation of Engineering Materials, this paper presents procedures for estimating the magnitude of the effects of environment on creep-fatigue life. These procedures can also be used to predict the effect of other influences on cyclic life, such as heat-to-heat variations, degree of cold work, heat treatment, etc.

The method of Strainrange Partitioning, SRP, Refs. (1-3), is used herein as the model for representing creep-fatigue resistance. Ideally, the SRP life relations would be determined for the material of interest, in its condition of interest, and in the environment of interest. The experimental procedures for obtaining the SRP life relations have been documented in Refs. (1-3). However, occasions arise for which it is economically impractical to expend the necessary time and effort to perform the required tests. A useful alternative would be to make engineering estimates of the life relations.

The procedures for estimating the four SRP life relations involve the use of correlations established between the SRP lines and ductility or true strain at fracture, D, as determined from measurements of reduction of area, RA, in conventional short-time tensile and monotonic creep-rupture tests; $D = -\ln(1-RA)$. The life relations are in the form of the Manson-Coffin equation for low-cycle fatigue and are referred to as the Ductility Normalized-Strainrange Partitioning, DN-SRP, life relations. A knowledge of the tensile plastic ductility, D_P, and the creep-rupture ductility, D_c, measured in the environment of interest and on the material in the conditions of interest is all that is needed to make a first order engineering estimate of the SRP life relations of an alloy.

If, for example, the SRP life relations were desired for a material that was to be used in a high temperature flue-gas environment, a first order estimate of these life relations could be obtained from creep and tensile ductilities measured in the same flue-gas environment. Similarly, if SRP life relations were desired for a material to be used in a vacuum or in a radiation environment, tensile and creep ductilities would be measured in the vacuum or for the irradiated material, and the SRP life relations estimated from these measured properties. In this way a relatively simple and inexpensive test can be substituted for the more complex creep-fatigue tests.

Examples were taken from the literature for several high temperature alloys including austenitic stainless steels and a cobolt-base alloy. These had been exposed to creep-fatigue loading in oxidizing and reducing environments. Cyclic lives were predicted from a knowledge of the ductility properties in the test environment.

Ductility Normalized-SRP Life Relations

The concept of expressing low-cycle fatigue equations in terms of ductility dates back to the 1950s. At low temperatures below which creep is not expected to occur, tensile ductility has been correlated with low-cycle plastic strain fatigue by a number of investigators including Coffin

(4), Manson (5,6), Halford and Morrow (7), Martin (8), etc. At elevated temperatures, similar types of equations have been used by Halford and Manson (9), Coffin (10), Berling and Conway (11), Spera (12), and others. More recently, we have proposed, as reported by Manson (2), a set of life relations (based on the limited SRP data available in 1972) which relate tensile and creep-rupture ductilities to the four SRP life relations.

Since that time, additional SRP and ductility data have been generated which have been examined by the authors to arrive at a more refined set of ductility normalized life relations. The resultant up-dated DN-SRP life relations, which are intended for use with the interaction damage rule (2) are presented below and displayed in Fig. 1.

$$N_{pp} = (2\Delta\varepsilon_{pp}/D_p)^{-1.67} \tag{1}$$

$$N_{pc} = (4\Delta\varepsilon_{pc}/D_p)^{-1.67} \tag{2}$$

$$N_{cc} = D_c(4\Delta\varepsilon_{cc})^{-1.67} \tag{3}$$

$$N_{cp} = D_c(5\Delta\varepsilon_{cp})^{-1.67} \tag{4a}$$

$$\text{or} \quad N_{cp} = D_c\ (10\ \Delta\varepsilon_{cp})^{-1.67} \tag{4b}$$

The expression, Eq. (4a), for the CP life relation is intended for application to materials which fail by a transgranular mode of cracking during creep, such as was observed for 2-1/4 Cr-1 Mo steel (1). Equation (4b) is intended for application to materials such as austenitic stainless steels (1) which typically experience intergranular cracking during creep. As used in this paper, creep strain is the thermally activated time-dependent strain (transient plus steady state plus tertiery creep).

The differences between the previously proposed (2) life relations and the current DN-SRP life relations are not fundamental; only the magnitudes of the constants have changed, i.e., the values of the exponents (slope) and intercepts (inelastic strainrange at one cycle) have been changed to reflect the average trends of the larger data base now available. It should be noted that a common slope is now used for all four life relations. As with the originally proposed relations, the DN-SRP life relations employ tensile plastic ductility, D_P, to estimate the life relations involving time-independent plastic strain in the tensile half of the cycle (PP and PC type cycles) and creep-rupture ductility, D_c, is used in the two relations involving time-dependent creep strains in the tensile half of the cycle (CP and CC type cycles).

Since the ductility of some materials varies with exposure time at temperature, the question arises as to what value of ductility to use in the DN-SRP life relations. Manson (13) deals with this question in considerable detail. It appears to be reasonable to use the ductility corresponding to the specific failure time of interest. The technique involves an iterative type of calculation to adequately characterize the ductility and is fully described in (13).

Space limitations do not permit a thorough documentation of the current SRP and ductility data that have gone into the reformulation of the DN-SRP life relations. Nor is space available to review the many features of the method of SRP which are described in more detail in Refs. (1-3).

Application of DN-SRP Life Relations

Not only can the DN-SRP life relations be used for estimating the effects of environment on cyclic life, they may also be used to approximate the effect on cyclic life of other important variables such as long-time exposure, radiation damage, temperature of exposure, heat-to-heat variations, heat treatment or fabrication condition, etc. During preliminary design, there is frequently insufficient time to undertake a testing program that would yield the desired experimental creep-fatigue results in the environment of interest, for the time span of interest, and for the exact material and material condition of interest. Hence, extrapolation of some sort must be made, and the DN-SRP life relations provide a tool for this extrapolation.

Three levels of sophistication in the application of the DN-SRP life relations are illustrated in this paper using laboratory specimen data taken from the literature.

Level I - SRP Life Relations from Ductility Data Only

For example, if no cyclic data are available and there are no prospects for their immediate generation, the life relations must be based on plastic and creep ductility information generated in the environment of interest. Obviously, any life predictions resulting from the use of these values in Eqs. (1-4) will be, in general, the most approximate of any. Nevertheless, an approximate answer can often suffice.

To illustrate how the DN-SRP life relations are used to predict cyclic lives, and how well predictions agree with observed lives, we have selected two sets of laboratory data for which sufficient information is available to permit a thorough analysis. The first set of data is for the cast cobalt-base superalloy, MAR-M302, for which high-temperature, low-cycle creep-fatigue tests were conducted at the NASA Lewis Research Center. All tests were conducted in a still air environment at 1000 C. Sufficient information was obtained during testing to permit identification of the strainrange fractions, F, in the interaction damage rule (2):

$$F_{pp}/N_{pp} + F_{cc}/N_{cc} + F_{pc}/N_{pc} + F_{cp}/N_{cp} = 1/N_{PRED} \qquad (5)$$

Selecting one of our tests as an example, the following partitioned strainrange data were obtained.

$$\Delta\varepsilon_{in} = 0.0026$$

$$F_{pp} = 0.40, \; F_{cc} = 0$$

$$F_{cp} = 0.60, \; F_{pc} = 0$$

A knowledge of the SRP life relations is now needed to evaluate the PP and CP lives thus permitting the solution of the interaction damage rule equation. Since the SRP life relations were not known from cyclic experimental information, it was necessary to estimate them from the DN-SRP life relations. Plastic and creep ductility data for this alloy were reported by Fritz and Koster (14) in a recent NASA contractor report. At 1000 C, $D_p = 0.29$ and $D_c = 0.26$ (at 6.4 hrs.). In the present case, the creep ductility was a decreasing function of time to rupture. In estimating the CP life relation for a test duration t_f, a creep ductility corresponding to a rupture time equal to t_r was used. Examination of the creep-rupture and cyclic specimens involving a CP strainrange component indicates that this alloy experienced intergranular cracking during creep. Hence equations (1) and (4b) were used to evaluate the PP and CP life relations:

$$N_{pp} = 0.04 \, (\Delta\varepsilon_{pp})^{-1.67}$$

$$N_{cp} = 0.006 \, (\Delta\varepsilon_{cp})^{-1.67}$$

Using these life relations along with the partitioned strainrange fractions noted above, we obtained a predicted life of 174 cycles (6.4 hrs.). The observed life was 337 cycles.

The remainder of the cyclic tests for the MAR-M302 alloy were analyzed in the same manner as above. A comparison of predicted and observed cyclic lives is summarized in Fig. 2. Of the 17 tests with this alloy, the cyclic lives for all but two of the tests were predicted within factors of three.

The second set of cyclic life results to be predicted using ductility data only is for annealed type 304 austenitic stainless steel tested at 650 C in a still air environment (15). These results are of particular significance since they represent the longest duration (230 to 4600 hrs.) creep-fatigue tests ever to be conducted under controlled laboratory conditions on this technologically important alloy. Specific details of the cyclic tests which were provided by Curran and Wundt (16) enabled us to determine the inelastic strainranges and partitioned strainrange fractions for each test.

All tests involved only PP and CP strainrange components in varying combinations. Using the 650 C plastic ductility and creep ductility values also supplied by Curran and Wundt (16), the pertinent DN-SRP life relations, Eqs. (1) and (4b), were evaluated. Again, the creep ductility in the time span of interest was a decreasing function of time to rupture, and the creep ductility, D_c, for Eq. (4b) was determined by using the duration, t_f, of the cyclic test.

The interaction damage rule, Eq. (5), was again used in computing the predicted lives for each cyclic test. Figure 2 also summarizes the predicted and observed cyclic life results for the 304 stainless steel. For the 14 tests with this alloy, we were able to predict the cyclic lives of of 12 within acceptable life factors of three.

Level II - SRP Life Relations Scaled by Ductility Ratios

More confidence in life predictions by using the DN-SRP procedure can be obtained by utilizing cyclic data previously generated on a different heat of the same material, or at a different temperature, or even in a different environment. In a case of this nature, the measured life relations could be scaled along the strainrange axis by the ratios of the ductilities between the two conditions in accordance with Eqs. (1-4). It is this ability to shift the life relations generated under very specific circumstances to other sets of conditions that further enhances the engineering value of the DN-SRP procedure.

DN-SRP LIFE RELATIONS

To illustrate this procedure for estimating the SRP life relations, and these relations to predict cyclic life, we took advantage of the well documented SRP life relations for type 316 stainless steel generated at 705 C and reported by Saltsman and Halford (17). These life relations were then scaled by ductility ratios to match the conditions of the high-temperature, strain hold-time tests conducted by Brinkman, Korth, and Hobbins (18). The latter investigators conducted tests at a lower temperature (593 C) on a different heat of material (No. B65808), and reported sufficient information to determine the PP, CP, and PC strainrange fractions. These were used in the interaction damage rule, Eq. (5). An estimate of the necessary SRP life relations at 593 C for heat No. B65808 was obtained by noting the plastic and creep ductilities at this condition and at the 705 C condition for the NASA heat of material.

NASA Heat at 705 C	Heat No. B65808 at 593 C
$D_P = 1.03$, Ref. (14)	$D_P = 0.86$, Ref.(19)
$D_C = 1.47$, Ref. (14)	$D_C = 0.19$, Ref.(20)

In the lifetime span of interest (less than 250)hours), the creep ductilities were not a function of the rupture time for these two heats. Hence, a single value of creep ductility was used for each.

The ratio of the plastic ductilities for these two heats is 0.83 (0.86/1.03). The desired 593 C PP and PC life relations are then obtained by modifying (scaling), in accordance with Eqs. (1) and (2), the 705 C PP and PC life relations as reported in Ref. (17) by this 0.83 ratio.

$$N_{pp} = 0.222 \left[\frac{\Delta\varepsilon_{pp}}{0.83}\right]^{-1.709} = 0.163 \,[\Delta\varepsilon_{pp}]^{-1.709}$$

$$N_{pc} = 1.699 \left[\frac{\Delta\varepsilon_{pc}}{0.83}\right]^{-1.183} = 1.372 \,[\Delta\varepsilon_{pc}]^{-1.183}$$

Similarly, the ratio of the creep ductilities for these two heats is 0.13 (0.19/1.47). The desired 593 C CP life relation in obtained by modifying the 705 C CP life relation from Ref. (17) by this ratio in accordance with Eq. (4b).

$$N_{cp} = 0.024\ (0.13[\Delta\varepsilon_{cp}]^{-1.712} = 0.003\ [\Delta\varepsilon_{cp}]^{-1.712}$$

Armed with the appropriate life relations and a knowledge of the inelastic strainranges and strainrange fractions, life predictions have been made in accordance with Eq. (5) for the strain hold-time tests of (18). A comparison of the predicted and observed cyclic lives is shown in Fig. (3). Ninety two percent of the data fall within factors of three of the predicted lives. This must be considered as acceptable agreement.

Level III - SRP Life Relations With Measured PP Line

A third variation includes the use of a mixture of calculated DN-SRP life relations for PC, CC, and CP, and a measured PP life relation in the pertinent environment. The PP type tests are by far the quickest and least expensive to run of all the four generic SRP tests. If it is feasible to conduct a few cyclic tests of the PP type, the results can serve to "fix" one of the four SRP life relations. An alternative would be to use any relevent PP data published in the literature and scale the life relation to account for ductility differences. Estimations of the remaining three life relations can then be based on the previously discussed DN-SRP equations.

To illustrate the use of this procedural variation for predicting creep-fatigue lives, we have examined high-temperature, low-cycle fatigue data for three austenitic alloys, types 304 and 347 stainless steel and Incoloy 800. As dictated by this procedure, rapid, continuous strain-cycling (PP data) results reported in the individual references were used to establish the PP life relations. Reported values of plastic and creep ductilities are used to estimate the PC, CC, and CP life relations from Eqs. (2) to (4). In each case, appropriate detailed information has also been reported which has enabled the authors to make a determination of the partitioned inelastic strainrange fractions for use in the interaction damage rule. Specific details for each alloy are given below.

Type 304 Stainless Steel - Life predictions were made for the tensile strain hold-time (CP+PP) tests of this alloy at 593 C as reported by Brinkman and Korth (21) for four heats (No. 55697, 300380, 600414, 8043813) with a variety of heat treatments (as-received, re-annealed, aged). The investigators of (21) also reported rapid, continuous strain-cycling results. The PP life relation we used was based on rapid strain-cycling data from all heats and conditions since the effects of these variables on the PP life relations were negligible.

The creep ductility data needed to estimate the CP life relation from Eq. (4b) were reported by Sikka et al (22). Ductility data were reported for each of the four heats, but only for the as-received and re-annealed conditions. Hence, life predictions have been made only for these two conditions. For the times of interest, the creep ductilities were constant.

The predictions of cyclic life are compared with the observed cyclic lives in Fig. (4). Agreement is generally within factors of three or less.

<u>Type 347 Stainless Steel</u> - Following the same procedures as above, cyclic life predictions have been made for the compressive strain hold-time (PC+PP) results of Jaske et al (23) for type 347 stainless steel tested in a 760 C gaseous hydrogen environment. Exactly the same environment was used for measuring the plastic ductility and the rapid, continuous strain-cycling (PP) data needed to establish the PC, Eq. (2), and PP life relations for use in predicting life. Creep ductility data were not needed since neither CC or CP strainrange components were involved in any of the creep-fatigue tests being analyzed. Values of the partitioned strainrange components were reported by Jaske et al (23).

Results of the predictions are shown in Fig. 4 where observed cyclic lives are plotted versus predicted cyclic lives. Agreement is good. All of the predicted lives for this alloy are within factors of two of the observed lives.

<u>Incoloy 800</u> - Similar analyses have been made of the strain hold-time creep-fatigue results reported by Jaske et al (23) for heat No. HH8968 of the alloy Incoloy 800. Cyclic tests were conducted in a still air environment at temperatures of 538, 650, and 760 C. Plastic ductility values for each temperature were reported in the same reference, thus enabling the PC, Eq. (2), life relations to be estimated for each temperature. The PP life relations were measured directly at the same temperatures and have been reported by Conway et al (19).

Creep ductility values for use in estimating the CC and

CP life relations from Eqs. (3) and (4b) were not reported in either reference. Hence, a number of independent sources were consulted to document this needed property. Creep ductilities in the time span of 10 to 1000 hours were found to be a strong function of both temperature and rupture time, t_r ,as reflected in the following equations:

$$D_c = 0.18\ (t_r)^{-0.12} \qquad 538\ \mathrm{C} \tag{6}$$

$$D_c = 0.81\ (t_r)^{-0.15} \qquad 650\ \mathrm{C} \tag{7}$$

$$D_c = 2.70\ (t_r)^{-0.21} \qquad 760\ \mathrm{C} \tag{8}$$

The creep-fatigue tests of Jaske et al (24) included tensile strain hold-times (CP+PP), compressive strain hold-times (PC+PP), and tensile plus compressive strain hold-times. Adequate information was given to calculate the partitioned strainrange components. Again, the interaction damage rule was used to compute the predicted cyclic lives for each of the reported strain hold-time tests. Although agreement between predicted and observed lives was generally within factors of two in life, some of the tensile strain hold-time tests (CP+PP) at the lowest temperature of 538 C exhibited cyclic lives that were greater than the predicted lives by a factor of four. A possible explanation for these conservative predictions is the fact that by using Eq. (4b), we have assumed an intergranular mode of cracking for all of the tensile hold-time tests, regardless of temperature or hold time. It may be that the lowest temperature was not conducive to intergranular cracking. If so, then Eq. (4a) would have been more appropriate to use and the predicted lives would have more closely agreed with observed values.

CONCLUDING REMARKS

We have shown and illustrated by example a number of specific procedures for estimating the Strainrange Partitioning life relations of an alloy for use in predicting high-temperature, low-cycle, creep-fatigue lives. Other variations could be applied depending upon what experimental information is readily available or could be generated. What we have presented are three of the most basic procedures which can then serve as a starting point to guide others in the deployment of alternative variations. The procedures described for predicting life provided excellent (within factors of three) agreement with available creep-fatigue data.

Again, it should be emphasized that the most appropriate SRP life relations are those measured in the environment of interest, for the alloy of interest, at the temperature of interest, for the time of interest, etc.. Since, this luxury is seldom affordable, the simplified estimation procedures presented in this paper should be of significant value to the engineering community charged with the safety of structural components operating in high-temperature, creep-fatigue environments.

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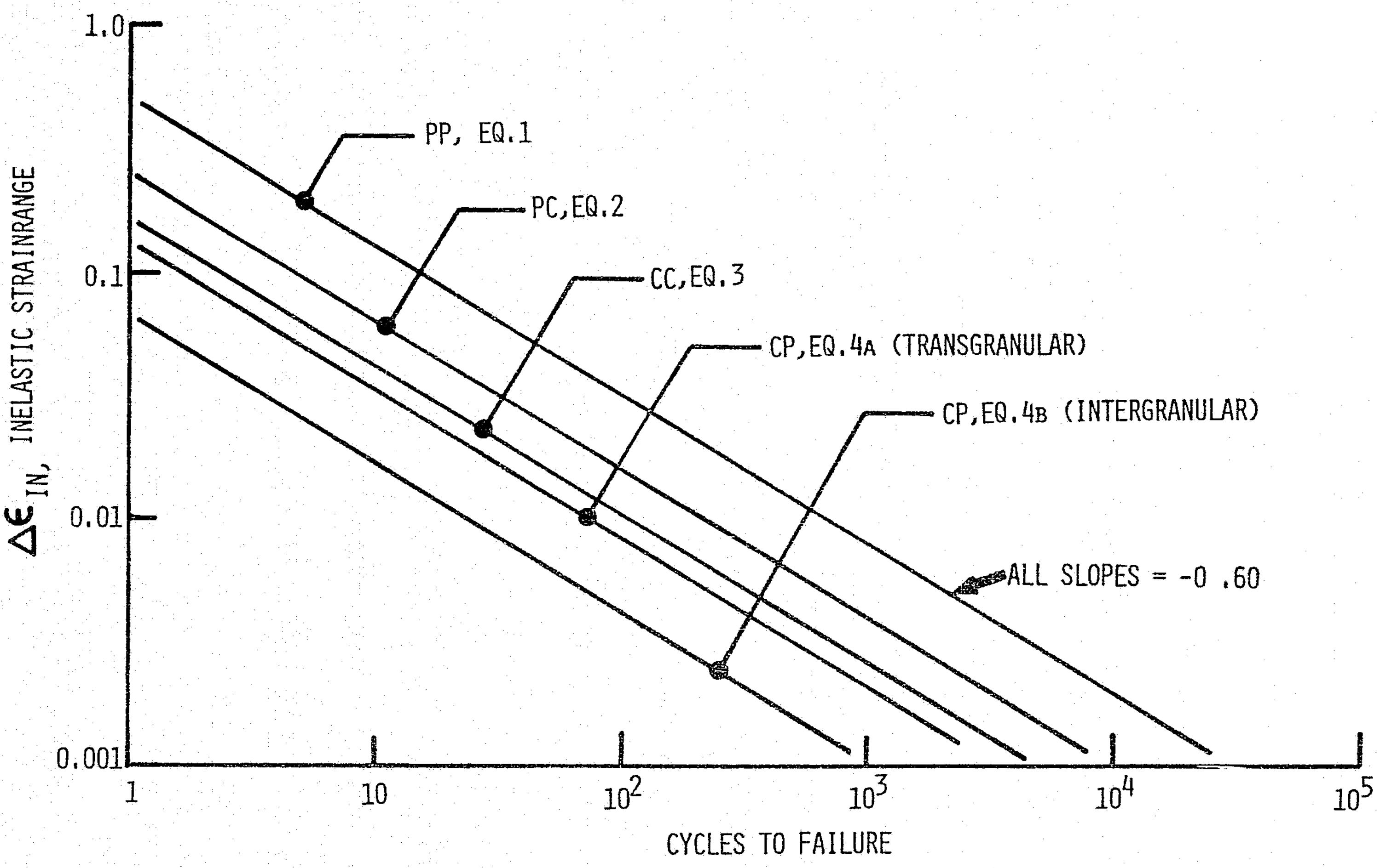
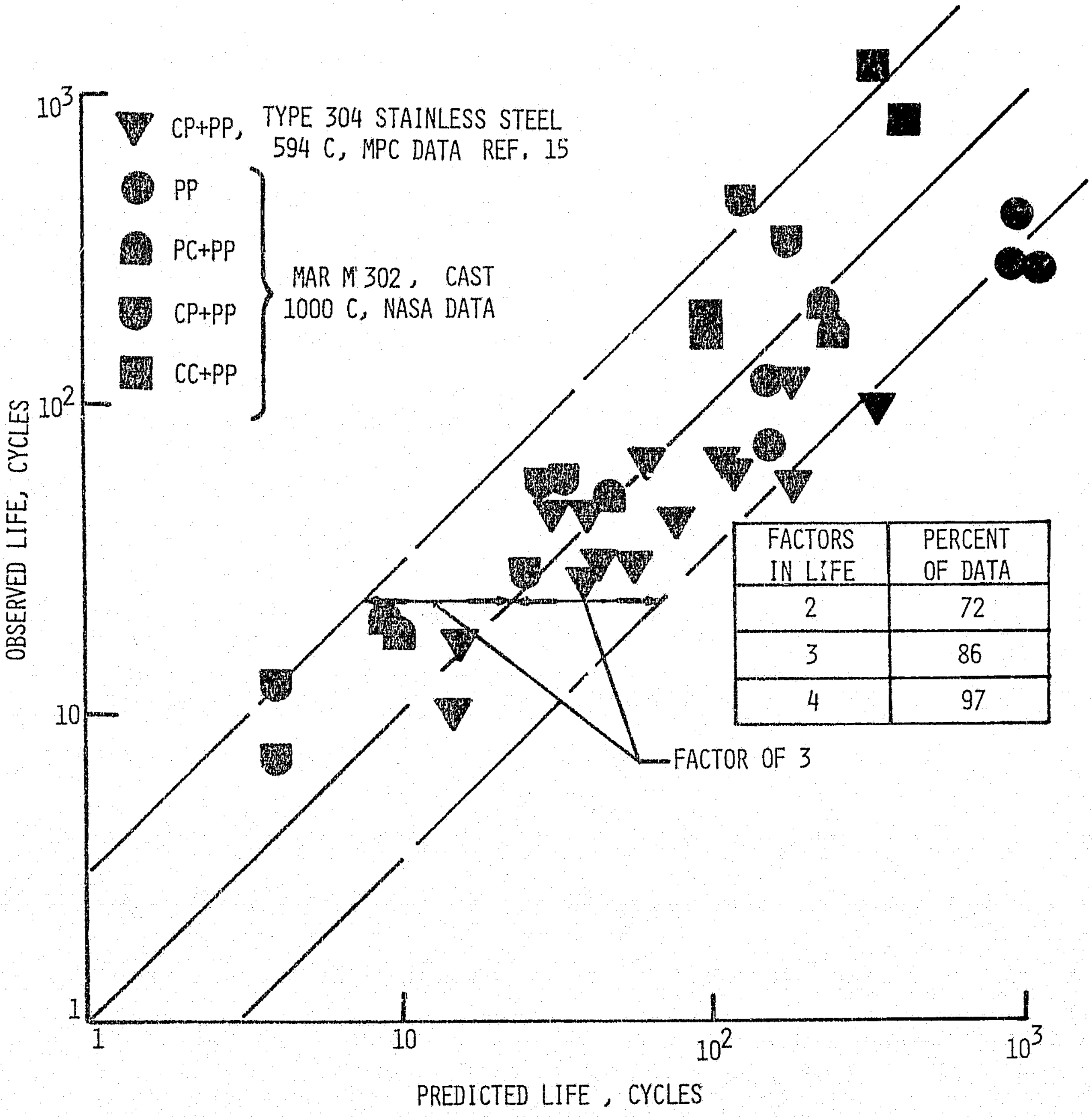
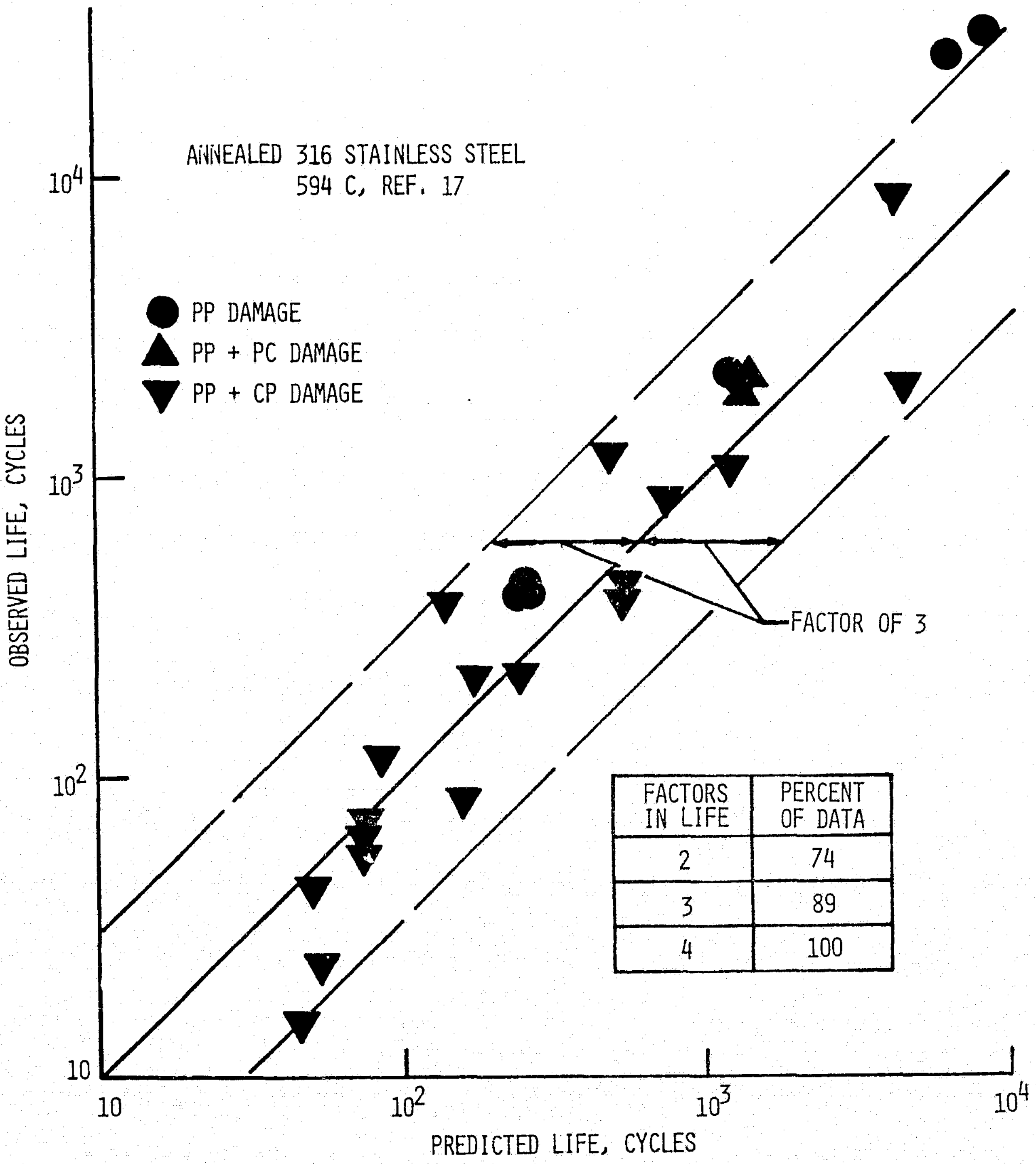


Fig. 1 - Ductility Normalized - Strainrange Partitioning Life Relations Evaluated for $D_P = 1.0$ and $D_C = 0.5$.



FACTORS IN LIFE	PERCENT OF DATA
2	72
3	86
4	97

ig. 2 - Comparison of Observed and Predicted Cyclic Lives for Two Alloys Based on the Ductility - Normalized Strainrange Partitioning Life Relations.



FACTORS IN LIFE	PERCENT OF DATA
2	74
3	89
4	100

Fig. 3 - Comparison of Observed and Predicted Cyclic Lives for Type 316 Stainless Steel. Predictions Based on Experimentally Determined SRP Life Relations Scaled According to Ductility Ratios.

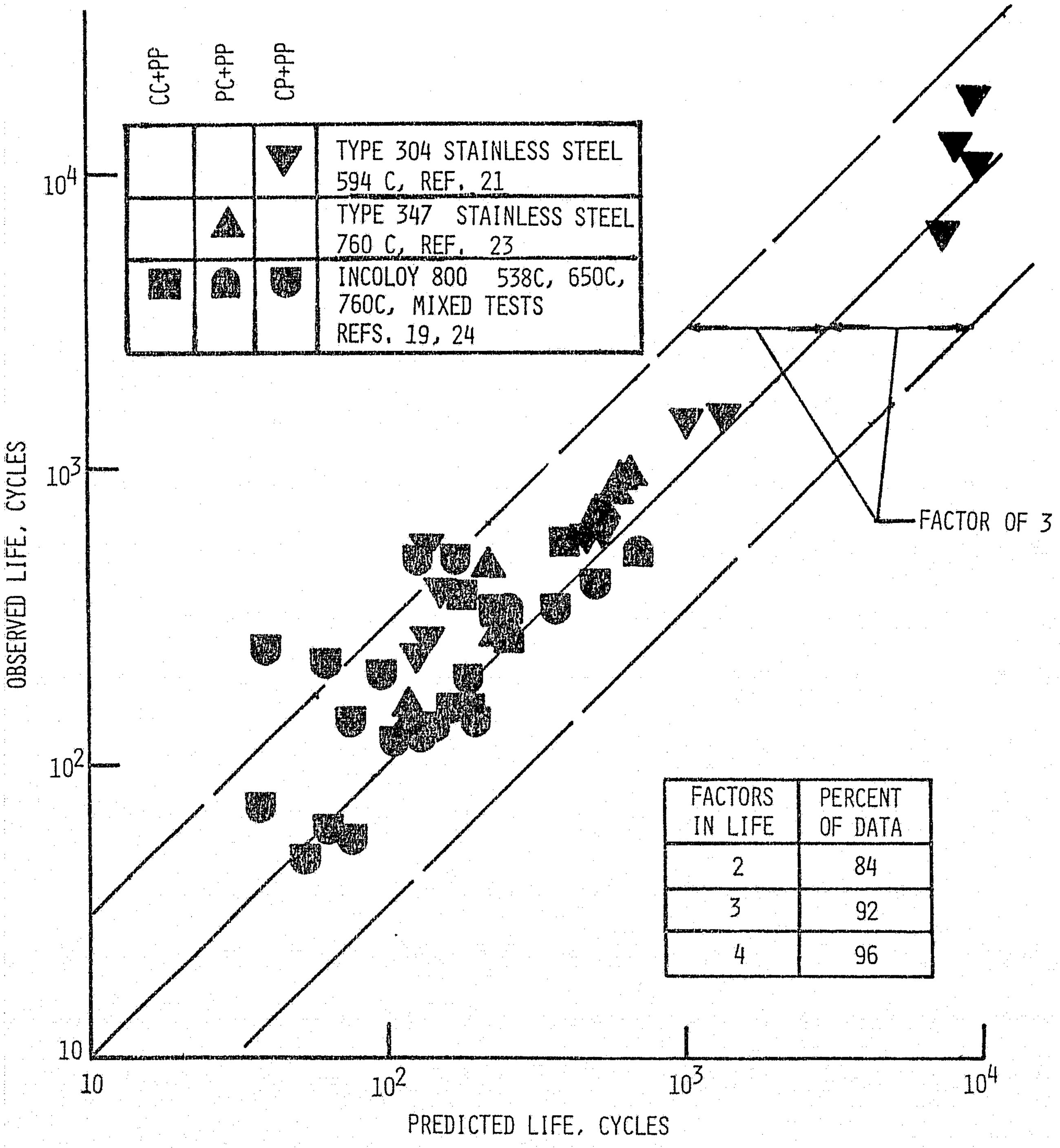


Fig. 4 - Comparison of Observed and Predicted Cyclic Lives for Three Alloys. Life Relations Based on Ductility Normalized Equations with Measured PP Line.