

TENSILE AND COMPRESSIVE CONSTITUTIVE RESPONSE OF 316 STAINLESS STEEL AT ELEVATED TEMPERATURES*

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ABSTRACT

It is demonstrated that creep rate in compression is lower by factors of 2 to 10 than in tension if the microstructure of the two specimens is the same and they are tested at equal temperatures and equal but opposite stresses. Such behavior is characteristic for monotonic creep and conditions involving cyclic creep. In the latter case creep rate in both tension and compression progressively increases from cycle to cycle, rendering questionable the possibility of expressing a time-stabilized constitutive relationship.

The difference in creep rates in tension and compression is considerably reduced if the tension specimen is first subjected to cycles of tensile creep (reversed by compressive plasticity), while the compression specimen is first subjected to cycles of compressive creep (reversed by tensile plasticity). In both cases, the test temperature is the same and the stresses are equal and opposite. Such reduction is a reflection of differences in microstructure of the specimens resulting from different prior mechanical history. If specimens of identical microstructure are tested in tension and in compression, large differences in creep rate are again evident, whether that microstructure was developed by prior loading in tensile creep/compressive plasticity or by tensile plasticity/compressive creep. The significance of the differences in creep rate under tension vs. compression, as related to the development of constitutive relationships for creep-fatigue problems, requires further study.

Little research has been conducted to explain the physical basis for this behavior. Several speculative reasons are offered, but require verification.

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INTRODUCTION

It is common to assume that the creep characteristics of metals in compression are similar to those in tension. Such an assumption derives from the fact that the time-independent deformation characteristics in tension and compression are similar. Very few experimental programs have, however, been conducted to determine the validity of presupposing similarity of creep characteristics.

In the course of our studies of Strainrange Partitioning over the past decade it has become clear to us that the differences between tensile and compressive creep rates at the same stress level can be appreciable, at least for 316 stainless steel, which we have investigated most extensively. The early tests in 1971 [1] on cyclic creep were very revealing in this respect. These tests will be discussed later in this report. Loading was first in tension, allowing creep to develop a pre-specified strain. The stress was then reversed to a compression of equal magnitude, and this stress was maintained until the compressive creep strain completely reversed the tensile strain. In many cases the time required to produce the compressive creep strain was as much as a factor of three or more higher than that to develop the tensile creep strain. This long time was, in fact, the basis for conducting what turned out to be the first cp test (in Strainrange Partitioning terminology [2]) when an attempt was made to reduce the unacceptably long times required to reverse the tensile creep by imposing much higher compressive stress which reduced the reversal time essentially to zero.

In addition to the experience with the cyclic creep tests, we have observed in a number of other test programs that the compressive creep rate at a given stress level is lower than the corresponding creep rate at an equal tensile stress. It is the purpose of this paper to outline the results of some of these experiments. Though the difference between tensile and compressive creep strain rates is not necessarily of great importance in many aspects of formulation of the constitutive relations discussed in this Conference, it may be of significance in some cases, as will be illustrated later.

The micromechanistic reasons for the differences in creep rates have not been extensively investigated; in this report we offer several speculations which, of course, require verification.

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EXPERIMENTS INVOLVING DIFFERENCES BETWEEN TENSILE AND COMPRESSIVE CREEP RATES

The following discussion relates to observations wherein appreciable difference was observed between tension and compression creep rates. Although most of the results shown involve AISI 316 stainless steel, we have also observed the effect in a limited number of other materials, which leads us to speculate the phenomenon is a general one, the magnitude of the effect varying, of course, among materials.

A. CYCLIC CREEP RUPTURE TESTS

a) Background

Reference to these tests has already been made in the Introduction. They were initiated in an effort to improve the time-and-cycle approach for treating creep-fatigue, as discussed in Ref. 1. In this approach creep damage is taken as the ratio of time at which a given stress and temperature is imposed divided by the creep-rupture time at the same stress and temperature. Because the use of monotonic creep-rupture tests often gives poor results when so applied, and in recognition that creep-fatigue tests involve cyclic variations of stress, our hypothesis was that cyclic creep rupture tests would produce improvements in predictions made by this method. Reference 1, in fact, demonstrates the validity of this hypothesis.

The type of test adopted for obtaining cyclic creep rupture tests is shown schematically in Fig. 1. The loading was generally started in compression to insure that the stress level chosen would not immediately produce a run-away creep strain. As shown in Fig. 1(a) the selected stress was held constant until a specified total strain was reached, usually of the order of 1 to 2%. The time required is shown as AB in Fig. 1(a), and the strain pattern is shown by the curve OAB. At point B the stress was reversed to tension, and this stress was held constant until an equal tensile strain was reached. The stress and strain pattern during this period are shown as BCD in Figs. 1(a) and 1(b), respectively. The pattern of reversal of equal stresses and strains in tension and compression was repeated successively as shown in Figs. 1(a) and 1(b) for as many cycles as were required to rupture. The hysteresis loop followed in all cycles was essentially OABCD of Fig. 1(c).

The results of these tests are shown in Fig. 2, representing a plot of stress versus rupture time, as in conventional creep-rupture plots. Monotonic creep-rupture is shown by curve M. When only the tension time of the test is used (neglecting the reversal time in compression), the results are shown by curve N. In the analyses of Ref. 1 we found good agreement between predictions and experiments when several types of creep-fatigue tests were analyzed using the creep rupture curve N in the "time-fraction" terms. The total time curve P, which includes the compression time, did not prove as useful as curve N in the analysis, and its development required excessively long times.

As can be seen from Fig. 2, factors as high as 5 or more existed between P and N. In order to minimize the test time a type of loop shown in Fig. 3 was developed. The compressive stress pattern BCE was introduced, reversing the creep strain AB by only essentially instantaneous plasticity. Thus the loop ABCDA (essentially what was later termed a cc loop in SRP terminology) was replaced by ABCEDA, later recognized as a cp loop (in the same terminology). While a small effect was produced on the tensile time creep-rupture curve N in Fig. 2, the curve so obtained for the cyclic creep rupture representation of the material was about equally suitable for creep-fatigue analysis by the time and cycle fraction method. Test time was, however, appreciably reduced.

b) Comparison of tension and compression creep rates

Since the tensile and compressive stresses were the same in the cc loops, and since the temperature was held constant, the results of these tests provide direct data for comparison of creep rates under the two loading conditions. Some of the data used are shown in Fig. 4 which is a scale plot analogous to the schematic of Figs. 1(a) and 1(b). Fig. 4 shows two effects on creep rate.

First, it is noted that both tension and compression creep rates vary as a function of time (or applied cycles). The time required to complete the first cycle is nearly a factor of 10 longer than the time required to complete the 90th cycle in this test which ran 98 cycles to cause rupture. In each cycle the time required to complete the tension creep is considerably shorter than the time required to complete the compressive creep of equal magnitude. Thus there are two major effects: the relation between the tensile and compressive creep rates in any single cycle, and the relations among the tensile and compressive creep rates in successive cycles.

The complete analysis of results shown in Fig. 4 is given in Fig. 5. Here both the tension and compression creep rates are plotted as a function of cycle ratio. It is clear from this figure that both the tensile and compressive creep rates increase as cycle ratio increases, varying by as much as a factor of 10 from the first cycle to the last few cycles. Similarly, it is clear that the tensile creep rate is higher than the compressive creep rate in each cycle. The compressive creep rate is, on average, about 1/3 as high as the tensile creep rate.

An additional test which shows similar results is shown in Fig. 6. This figure also clarifies how creep rates were determined without introducing error associated with cross-sectional changes that are different in tension and in compression. Figure 6(a) shows the hysteresis loop. By measuring the tensile creep rate at point E where the strain is zero, and the compressive creep rate at point F where the strain is also zero, true creep rates are determined, since the cross-sectional areas were exactly the same at the two points in the cycle. The creep rates are shown in Fig. 6(b). The tensile creep rate is

again seen to be two to three times as high as compression. Although the steepness of rise in creep rate in the later cycles gives the illusion that the two curves are approaching each other, the difference by a factor of two to three persists until near-failure, as can be determined by measuring vertical distance between the two curves. Since the vertical scale is logarithmic, this constancy of vertical displacement implies a constant ratio between the two values.

c) Significance of results

These results show not only that creep rate in tension differs from that in compression, but that both rates vary significantly during the lifetime, even for this simple repetitive loading pattern. Attempts to develop constitutive equations that will be applicable throughout the life should be in harmony with this simple observation.

On the other hand, it should be pointed out that stabilization has readily been achieved in many SRP strain cycling tests involving creep in only one direction. Thus while some caution is required in seeking constitutive relations involving reversed creep, the more practical applications in which the major creep component occurs only in one half of the cycle (tension or compression) does not seem to involve this complication.

B. CONSTANT LOAD TESTS

Another series of tests we have conducted in which differences in tensile and compressive creep rates have been observed relate to ordinary static creep under constant load. The results are described below.

a) Specimen Stabilization

In these tests the specimens were first stabilized relative to cyclic plastic strain by the scheme shown in Fig. 7. The strain amplitude was first gradually increased to 1% while cycling at a frequency of 0.20 Hz. Then 30-40 cycles of the 1% strain amplitude was applied, after which the strain amplitude was reduced during cycling in a manner symmetrical to the forward-loading. The cycles at constant $\pm 1\%$ strain stabilized the material and established a repetitive hysteresis loop, similar to the manner a material is normally stabilized in room temperature fatigue to establish a cyclic stress strain curve. Such curves do not significantly reflect the hardening or softening characteristic of the early loading cycles. The stabilization was initially introduced because the intended purpose was to develop a constitutive creep model for the material for later use in creep-fatigue analysis. Thus it was thought appropriate to decouple the cyclic creep effects from the cyclic plasticity effects. In the present discussion we are concerned only with the static creep behavior of the stabilized material.

Fig. 7(b) shows the hysteresis loops developed during the increasing amplitude straining (continuous lines), the stabilized hysteresis loop (heavy line), and the decreasing amplitude straining (dotted lines). It is clear that in the final state the net stress and strain are both zero. Thus the creep tests which follow are on specimens which have neither residual stress nor residual strain nor do they have a memory of prior straining in one particular direction. Since the stabilization cycling is very rapid, there is essentially no creep damage on the test specimens. Also, since the specimen can withstand about 15 such blocks as shown in Fig. 7(a), the amount of fatigue damage is

also small.

b) Correction for cross-sectional area changes

Typical creep curves obtained are shown in Fig. 8 which are for a nominal 18 ksi stress in tension and compression at 1300F. While the creep curve OAB in tension is clearly higher than that in compression, part of the difference is due to cross-sectional area changes rather than inherent differences in creep characteristics at the two stress states. In tension the cross-sectional area continuously decreases as the strain increases. Thus, for the constant load (nominally 18 ksi for the original cross-sectional area) the true tensile stress is continuously increasing.

The compression creep curve OA'B' involves an increasing cross-sectional area which reduces the true compressive stress.

If we assume that creep rate at constant temperature is proportional to a power law of stress σ^m we can correct the tensile creep rate at a strain ϵ by dividing by $(1+\epsilon)^m$ to obtain the rate that would have been observed if the stress had been kept constant by reducing the load progressively. Similarly, for the compressive strain the creep rate must be divided by $(1-\epsilon)^m$ to obtain the appropriate strain-independent creep rate.

c) Test results

Figure 9 shows the results for tension and compression for a number of creep tests conducted at several stress levels in both tension and compression. Approximate straight lines can be drawn through the test results when steady state creep rate is plotted against stress on logarithmic scales. Thus a power law exists between the two variables. As seen in the figure strain rate for

both tension and compression vary as approximately the 11th power of stress, the multipliers being different depending on whether the loading is tension or compression, and whether the cross-sectional area correction is applied or not. However, even when the correction is applied, the creep rate in tension is about a factor of 5 higher than in compression. The "engineering" values, for which no correction is made, show differences of about a factor of 7.

d) Significance of results

These results show that, at least for 316 stainless steel at 1300F, it is inappropriate to develop constitutive relations based on the assumption that tensile creep rate and compressive creep rate are equal at the same stress and temperature. However, they also show that creep rate varies as the 11th power of stress. Thus, to maintain a creep rate in compression equal to that in tension it is necessary to increase the compressive stress by only a small amount. If, for example, the creep rate at a tensile stress of 40 ksi is to be reproduced as an equal value under compression, the compressive stress need only be increased to 46.40 ksi. When tests are conducted which are strain-controlled, forcing equal tensile and compressive creep rates will cause the compressive stress to be higher than the tensile stress (16% in the present illustration).

No reversed creep was involved in these tests. How the results would be affected by the presence of such creep requires further study. But from the results of Section A it is speculated that a significant effect could develop. Constitutive relationships for application to cyclic creep and plasticity might require appropriate recognition of this phenomenon.

C. THERMOMECHANICAL LOADING TESTS

Applications involving simultaneous variation in stress, strain, and temperature, commonly called thermomechanical loading, are among the most important cases for which constitutive modeling is required. Because a cooperative program between Case Western Reserve University and NASA-Lewis is currently underway, it is appropriate to include here some of the results which are pertinent to the question of the relation between tensile and compression creep characteristics.

a) Tests in progress

Figure 10 shows some of the control patterns of tests that are in progress. These tests use AISI 316 stainless steel specimens, not, however, stabilized according to the pattern of Fig. 7. In one type of test, Fig. 10a, the strain and temperature are cycled in-phase, high temperature and tensile stress being achieved simultaneously. Such a loading usually develops cp type of strain because the highest tensile stresses occur while the temperature is high, causing creep, while the highest compressive stresses occur when the temperature is low so that no compressive creep occurs. In the second type of loading the strain and temperature are out of phase, producing net compressive creep because the temperature is high only when stress is compressive.

b) Creep rates during actual cycling

Ideally, it would be desirable to compare the creep rates of the specimens at the same temperatures and at equal but opposite stresses at appropriate points in the in-phase and out-of-phase cycling where such conditions develop. Unfortunately, such conditions do not develop for the very reason that compres-

sive creep response differs from the tensile creep response. This fact can be seen in Fig. 11 which shows the stresses developed at each temperature during the in-phase and out-of-phase tests. If tensile and compressive creep response were similar, the two curves would be mirror images of each other with respect to the horizontal axis. The fact that the compressive stresses reached are higher than the tensile values, verifies that creep rates at a given stress and temperature are lower in compression than in tension. Thus, to maintain the equal strain rates imposed, a slightly higher stress develops during the out-of-phase loading tests, as is clear from Fig. 11. From this figure it can be seen, then, that it is not possible to compare directly specimens taken from each of these tests when they are at the same temperature and at stresses which are equal but of opposite sign.

By writing analytical relations for creep rates in the two tests in terms of stress and temperature, it is possible, however, to calculate the creep rates at the same stress in tension and compression. Several forms of constitutive relationships have been studied; we consider here only the simplest type taken in the form of the Arrhenius equation

$$\dot{\epsilon} = A \sigma^m e^{-\frac{\Delta H}{RT}} \quad (1)$$

Analyses were made using the in-phase data only, the out-of-phase data only, and combining all the data into one correlation. A complete discussion of all the results will be published when the program is completed; the tentative results pertinent to the current subject will be discussed only briefly.

Using the common formulation of all the data, including both the in-phase and out-of-phase results, the equation becomes:

$$\dot{\epsilon}_{SS} = (123.832)\sigma^{10} \exp\left(\frac{-180633}{T}\right) \quad (2)$$

where σ = stress, ksi

T = temperature, degrees R

$\dot{\epsilon}_{SS}$ = creep rate per sec.

Fig. 12 shows the correlation between the experimental creep rates measured in both the in-phase and out-of-phase tests and the computations based on Eq. (2). The agreement is quite good, suggesting a common constitutive relationship for both tension and compression creep rates as a function of stress and temperature. While this result is very satisfying from the analyst's view of desiring to neglect differences between tensile and compressive constitutive behavior, it seems to negate the findings about the differences discussed. In order to clarify the apparent discrepancy additional tests were conducted as discussed in the next section.

c) Creep rates at approximately constant microstructure

The microstructure of a specimen sampled at a point of tension during the in-phase loading can be considerably different from the microstructure of a specimen sampled from an out-of-phase test at the same temperature (and approximately equal and opposite stress). Thus, although it is fortuitous that the same equation can be used to determine the strain rate of both specimens, the equality of tensile and compressive creep rates does not negate our general

finding that compressive creep rate is lower than the tensile creep rate at the same temperature and equal but opposite stress. To determine if this finding is general, and still valid for material in thermomechanical loading, it is necessary to conduct tests in tension and compression of material in the same microstructural state. Ideally, a scheme such as shown in Fig. 13(a) would be suitable for this purpose. The hysteresis loop represents the path, for example, of in-phase loading. At point A the thermomechanical loading is discontinued, and temperature and stress are "frozen" and maintained constant at the value achieved at this point. By holding the stress constant, creep strain occurs along AB as a function of time as shown in Inset I of Fig. 13(a). The steady state creep rate which develops is then characteristic of the tensile creep behavior of the material in its microstructural condition at A. To obtain the compressive creep characteristic we should, ideally, use a second specimen, stabilize the loading loop by applying the same number of cycles, stop again at point A, and then reverse the stress to an equal but opposite value, maintaining the temperature. The path A'B', both on the stress-strain diagram, and the strain-time diagram of Insert II then represents the compressive characteristic of the material in its microstructure of point A. The creep curves of Inserts I and II provide the needed comparison of tension and compression for a material in the same microstructural condition.

The scheme actually used in this program is shown in Fig. 13(b). A single specimen was first crept along AB, after which the load was reversed to an equal but opposite value, and the compressive creep characteristic A'B' was obtained. This procedure was used for two reasons: conservation of specimens, and avoiding the possibility of scatter resulting from using separate speci-

mens. Actually, then, a small change in microstructure was introduced by the tensile creep AB for the material subsequently tested along A'B'. However, the economy and efficiency of using a single specimen was deemed sufficient to justify the alternate approach in the preliminary tests. Furthermore, our expectation was that the compressive creep rate would be lower than the tensile creep rate. Since it is reasonable to assume that the prior tensile creep AB would, if it had any effect, accelerate the compressive creep rate (in accordance with the results of Figs. 1-3), any observed lower creep rate in compression would in fact be accentuated were the prior tensile creep not imposed.

A number of tests of the type described above were conducted, stopping at various points in the in-phase loading loop. Similarly, analogous tests were conducted by stopping at selected points of compressive stress in the out-of-phase loading, and conducting tests in both compression and tension for microstructures developed in these tests. Typical results shown in Fig. 14(a) relate to one of the tests for in-phase loading; Fig. 14(b) displays results for out-of-phase loading. It is clear that in both cases the creep rates in compression are significantly lower than these in tension. The other tests corroborated these observations.

We can conclude from this study that the generality holds for material in thermomechanical tests, namely that if material is sampled from any point in its path and tested both in tension and in compression, the tensile creep rate will be considerably higher than the compressive creep rate. The two tests must, however, be conducted on material in the same microstructural state.

D. CYCLIC LOADING OF HASTELLOY X

It is interesting to study the results of Walker [3] on Hastelloy-X to ascertain whether the general behavior observed on 316 SS also applies to his material. Some of his test results are shown in Fig. 15. Discussion of the results of his calculations based on the Functional Theory are beyond the scope of this paper. However, the experiments are amenable to analysis for the present purpose.

Walker's tests were conducted on a specimen which was continuously cycled at a constant strain rate, stopping at various points to establish the creep rate for the material in its current metallurgical state. After each creep loading at constant stress, the loop was re-stabilized before proceeding to the next point. Thus the creep tests were on materials in different metallurgical states, and direct comparison of tension and compression involves the difficulties already discussed in connection with Fig. 2. However, it is still instructive to make the comparison because the careful experiments do reveal differences in the two creep rates.

The continuous curves of this figure show experimental creep curves at various stresses. Some are tension creep curves, others compression. While the comparison can be made by direct examination of the curves of Fig. 15, the cross-plots of Figs. 16 and 17 are more convenient for quantitative comparison.

Fig. 16 shows the cross-plot of stress versus strain after 40 seconds. OA shows the strain developed after this time for tensile loading, OB the strain for compression loading, for each of the stress levels studied. The dotted curve OB' is a replot of OB, changing signs of both stress and strain. By comparing OA to OB' it is clear that at any stress level the amount of strain in

tension is more than that in compression after the 40 sec. used as a parameter. The cross-plot of Fig. 17 shows the ratio of strain developed in tension to that developed in compression after various times for the 21.5 ksi tests. While these results are not as dramatic as those we have obtained for 316 SS, it is quite clear that tensile creep rate is higher than compression creep rate at the same temperature but equal and opposite stress.

PARAMETERS THAT CAN AFFECT CREEP RATE AS A FUNCTION OF STRESS DIRECTION

The reason for the differences in creep rate at equal tensile and compressive stress has not received much attention. In fact, the phenomenon is not sufficiently well recognized to have stimulated study. We can only speculate at this time why the phenomenon exists. Following are some possibilities.

I. Effective Friction at the Grain Boundary

One way of viewing the problem is by analogy to friction of masses in contact moving relative to each other. Since creep frequently involves grains sliding along their boundaries we can regard the individual grain motion and the "friction" between them. The treatment is complicated, of course, by the fact that there are numerous grains oriented at numerous directions relative to each other. A simplified analysis is shown in Fig. 18 which assumes an average orientation of 45 degrees. Drawing the analogy with the movement of a weight on a frictional surface, shown in Fig. 18(a), we can see in Fig. 18(b) that the net frictional force is larger when two grains are in compression than they are when in tension. If we choose R as the ratio of the two forces, and assume

that the relative creep rate varies as some power law of R , we get the results shown in Fig. 18(c). The plot shows the relationship for different choices of μ and m . It is seen that reasonable choices of μ and m produce R values agreeing with our experimental results.

II. Change of Lattice Parameter

The size of the lattice increases in tension and decreases in compression. An effect can thus be produced on the creep rate according to the explanation given in Ref. 5:

"For close-packed crystals like fcc, hcp, the partial molar volume of vacancies is an appreciable fraction of molar volume of the metal. Under hydrostatic pressure in tension, the specimen will lose vacancies in an effort to relieve the pressure increase. This decrease in the concentration of vacancies will in turn decrease the self diffusion."

If creep rate is influenced by self-diffusion, as is commonly accepted, the hydrostatic compression should reduce creep rates and hydrostatic tension should increase creep rates.

III. Grain Boundary Cavitation:

At high temperature, cavities are generated in the grain boundaries which are in tension, facilitating the movement of one atom over the other, increasing in creep rate. In compression, however, the cavities are absent or collapsed even if activated previously in tension. This phenomenon is shown schematically in Fig. 19. Accordingly we can expect higher grain boundary creep when the net force across the grain boundaries is tensile than when it is compressive.

IV. Defects Other Than Grain Boundary Cavitation

Any defects developed in the microstructure of the material would tend to be open in tension and closed in compression, Fig. 20. Hence there would be greater tendency for reduction of cross sectional area in tension. Therefore the creep rate would be higher in tension than in compression.

CONCLUDING REMARKS

In all of the various types of tests that we have studied, tensile creep rate has always been higher than compressive creep rate if the loading is on specimens that have the same microstructure. This similarity of microstructure may be the result of absence of significant prior straining history, or it may be the result of a complex history of thermomechanical loading. Differences in creep rate from 2 to 10 have been observed. However, if the microstructure of the specimen to be tested in tension is different from that used in compression, the general pattern of behavior can be altered, although in the limited cases we have examined, there is still a bias toward lower creep rate in compression. Some of the effect is geometrical, -- tension producing a higher true stress because of decreases in cross-sectional area, while the area of a compression specimen increases. However, even when appropriate corrections are made for cross-sectional variations, the qualitative comparisons are not altered, although quantitatively the effect is somewhat smaller.

Of special interest is that the microstructure that develops during hysteresis cycling -- whether at constant strain rate and constant temperature, or whether the temperature variation is cycled in- or out-of-phase with the strain -- seems to be such as to bring closer together creep rates in the two direc-

tions when the tension specimen is taken at a point in the tensile part of the hysteresis loop and the compression specimen is taken at a point in the compression part of the loop. Whether there is a natural tendency for microstructure to develop to produce such a bias remains to be determined by studying additional loading patterns. From an engineering point of view, the effect is fortuitous because it makes more accurate the assumption usually made that the two creep rates are equal.

Even when there is an appreciable difference between the two creep rates at equal but opposite stresses, the error of engineering calculations based on the assumption of rate equality is mitigated by the fact that creep rate bears a high-exponent power law relationship to stress, so that only moderate changes in stress are needed to bring the actual creep rates to equality. Also, it is fortunate that in most of the important engineering problems involving stress and strain reversal, particularly thermal fatigue problems, the loadings are governed by imposed strains and strain rates. Thus the assumption that the stresses developed follow the same stress / strain / strainrate relationships in both tension and compression produces small error in the stress determinations. Were the loads specified, the errors in stress and strain rates would be much higher. The effect is further mitigated by the metallurgical tendency of microstructural development to more closely justify the usual engineering assumption.

Thus, while the effect of the phenomenon is somewhat suppressed in some practical engineering problems, its presence cannot be negated. As illustrated in this report at least some applications can better be understood in terms of the characteristic differences between creep rates in tension and compression.

Further experience may reveal other important applications. In any case it is an interesting phenomenon, both from mechanistic and analytical viewpoints, and it merits recognition, if not further study.

Finally, this study has led to a closer focus on a long-held observation that a combination of tensile and compressive creep produces an anomalous effect, at least on 316 SS. When creep is either absent or monotonic -- i.e. in pp, pc, or cp loading, we have usually found that after a few cycles of loading a stable hysteresis loop develops. Stress, strain become repetitive with respect to time as measured from some arbitrary point on the hysteresis loop. When reversed creep is present, i.e. involving cc loading, the temporal aspects of the loop are not repetitive. In the cases we have studied, extreme softening takes place, and an attempt to apply a single constitutive relationship to characterize all cycles could lead to significant error. The mechanistic effect here, as well as the mechanisms that cause creep rate in tension to be much higher than that in compression justify further study. Such study should lead to an improved understanding of the nature of creep in engineering materials and provide a useful input toward determination of appropriate time-dependent constitutive relations for handling reversed creep.