ORDER EFFECT OF STRAIN APPLICATIONS IN LOW-CYCLE CUMULATIVE FATIGUE AT HIGH TEMPERATURES

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SUMMARY

Recent test results on cumulative damage with two strain levels on a stainless steel (AISI 304) at room temperature, 537 and 650 °C show that the sum of cycle-ratios can be significantly smaller than unity for decreasing levels; the opposite has been noted for increasing levels. As a consequence, the use of the linear damage rule (Miner's law) for life predictions is not conservative in many cases.

Since the double linear damage rule (DLDR), originally developed by Manson *et al.* for room temperature applications, takes the order effect of cyclic loading into consideration, an extension of this rule for high temperature cases may be a potentially useful tool. The present paper is concerned with such an extension.

For cumulative damage tests with several levels, according to the DLDR, the summation is applied separately for crack initiation and crack propagation stages, and failure is then assumed to occur when the sum is equal to unity for both stages. Application of the DLDR consists in determining the crack propagation stage N_p, associated with a particular number of cycles at failure N, i.e. $N_p = PN^a$ where exponent a and coefficient P had been assumed to be equal to 0.6 and 14 respectively for several materials at room temperature.

When the DLDR is applied (with $a = 0.6$ and $P = 14$) to predict the remaining life at the second strain level (for two-level cumulative damage) for 304 stainless steel at room temperature, 537 °C and 650 °C, the results show that the damage due to the first strain level is over-emphasized for decreasing levels when the damaging cycle-ratio is small. For increasing levels, the damage is underestimated and in some testing conditions this damage is simply ignored. This predicted behavior is not in agreement with experimental data.

On the basis of available test results up to 650 °C, it has been found that:

a) a value of $a = 0.7$ (instead of $a = 0.6$) is more appropriate for strain-controlled conditions.

b) P is dependent upon the test temperature, the ratio between the strains imposed and the maximum strain level. Coefficient P may be regarded as the parameter taking into account the interaction effect which had been discussed extensively in cumulative damage tests.

With $a = 0.7$, new relations have been developed for calculating P, taking the above observations into consideration. For a given material, coefficient P depends mainly upon the testing conditions and its values range between 4 and 7 in the present evaluations.

The new set of values of a and P used with the DLDR provides estimates with an improved agreement with experimental data.

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1. Introduction

For cumulative damage tests under stress-controlled conditions at room temperature, there are several theories proposed in the literature which take into consideration the order effect of loading [1-3]. Recently, experimental results obtained at room temperature in low-cycle region have shown that the order effect of loading is significant whether the tests are stress- or strain-controlled [4,5]. Recognizing this fact, Manson et al [6] have proposed a double linear damage rule (DLDR) for fatigue applications. According to this proposition, the fatigue process should be divided into two phases, crack initiation and crack propagation, in which separate linear damage summation should be applied. Essentially, this DLDR would result in a sum of cycle-ratios greater than unity for increasing levels and smaller than unity for decreasing levels.

Recent data obtained from a stainless steel at high temperature with two strain levels [7] shows an order effect similar to that usually reported in the literature for tests at room temperature. Thus, the traditional linear damage rule suggested by Miner [8] may not be conservative for life predictions for decreasing levels.

The purpose of this paper is to examine whether a direct extension of the DLDR may be applied satisfactorily to cumulative fatigue damage problems with two strain levels at high temperature, and to discuss the dependency of the parameters involved in this rule upon the testing conditions.

2. Recent Experimental Data Obtained at High Temperature

A series of strain-controlled fatigue tests on a 304 stainless steel has been carried out recently at 20°, 537° and 650°C with a constant strain rate. After establishing the fatigue curves under isothermal conditions at these temperatures, tests with two strain levels have been performed either with an increasing or with a decreasing order of loading. More details on the experimental procedure, as well as a complete discussion on the test results may be found in [7]. Only typical data showing the order effect due to strain applications will be given here.

The order effect, as presented in Fig.1(a), 1(b) in which the sum of cycle-ratios at failure is plotted in terms of the cycle-ratio of the first level, may be summarized as follows:

(i) the sum of cycle-ratios is greater than unity for increasing strain levels and smaller than unity for the opposite case;

(ii) the deviation of this sum from unity depends upon the difference in the strain levels; the larger the strain level difference, the greater this deviation from unity.

In the following section, the DLDR will be examined by means of the test results already discussed.

3. Brief Review of the DLDR [6]

3.1 The rule

In the fatigue process, it has been proposed that the crack propagation period N_p be expressed in terms of the fatigue life N by the relation:

$$N_p = P\,N^a \qquad (1)$$

where P and a are constants.

It follows that the number of cycles required for the crack initiation stage, N_o, is given by:

$$N_o = N - N_p = N - PN^a \qquad (2)$$

Under tests with several levels, the DLDR has been suggested by making the summation separately for the two stages; failure is then assumed to occur when the sums are equal to unity for both stages. Thus:

(i) for the initiation phase:

$$\Sigma \frac{n_o}{N_o} = 1 \qquad (3)$$

(ii) for the propagation stage:

$$\Sigma \frac{n_p}{N_p} = 1 \qquad (4)$$

where n_o and n_p are the number of cycles applied at a particular level under the initiation and propagation periods respectively.

Manson et al further suggested that at a particular level corresponding to a value of N smaller than a reference value N_s the effective crack is presumed to exist upon the first cycle. Thus for $N < N_s$, $N_o \simeq 0$.

In the light of the results obtained from rotating bending tests on a 4130 soft steel for determining the crack propagation period, it has been proposed [6] that the numerical values of parameters a and P, taken as equal to 0.6 and 14 respectively, be valid for most materials; then, as a consequence, $N_s \simeq 730$ cycles.

With this set of numerical values of parameters, the deviation of the predicted fatigue behavior given by the DLDR from strain-controlled data is, in general, large [6,9]. This discrepancy may be seen typically in Fig.2, where the DLDR over-emphasizes the order effect of loading.

3.2 Direct extension for high temperature data

The DLDR is applied (with a = 0.6, P = 14 and N_s = 730) to calculate the remaining life at the second level for 304 stainless steel at 537°C and 650°C. The predicted values are shown in Fig.3 in comparison with the actual lives. It is seen that, when the value of n_1/N_1 is not large, the order effect evaluated by this rule, as was the case at room temperature, is:

(i) over-emphasized for decreasing levels; this means that the predicted remaining life is smaller than that actually obtained;

(ii) under-emphasized for increasing levels.

In particular, with increasing levels, the damage caused by the lower strain applications is partly ignored in some circumstances. Let us, for example, consider tests at 650°C with $\Delta\varepsilon_1 = 0.5$ percent and $\Delta\varepsilon_2 = 1.5$ percent. As long as the first cycle ratio n_1/N_1 does not exceed 0.53, according to this rule, no damage would be incurred to the material, a consideration which does not, in general, agree with experimental data.

3.3 Discussion of DLDR

Originally the DLDR was developed on the basis of experimental data mostly obtained under stress-controlled conditions. Since the order effect is, in general, less marked in test results with controlled strains than with controlled stresses [7], this rule may give large deviations in the life prediction for strain-controlled data.

Due to the fact that the predicted curves (strictly speaking, the broken straight lines) given by the DLDR are strain-dependent, the concept would be valid for life estimations in cases involving two strain levels. However, in order to obtain a better correlation, some refinement is required.

In the relation originally proposed for the crack propagation stage, i.e. eq.(1), a single combination of $a = 0.6$ and $P = 14$ has been suggested for many materials in both stress and strain-controlled conditions. Even for data obtained with controlled stresses, as given in Fig.7 of [6], for $a = 0.6$ each combination of two levels results in a particular value of P. This suggests that coefficient P or exponent a or both may be dependent upon several factors. Further details will be examined in the following section.

4. Examination of the Crack Propagation Equation

4.1 Value of N_s

In the evaluation of cumulative fatigue damage, it has been proposed in [6] that the crack propagation period only be considered for strain levels corresponding to $N < N_s$ ($N_s = 730$ cycles). This numerical value is determined by considering eq.(2) in order to have a positive value of N_o associated with $a = 0.6$ and $P = 14$. Modifying a and P will of course change the value of N_s.

4.2 Experimental curves

An investigation on the effect due to the variation of a and P reveals that a unique combination of these parameters would not improve significantly the correlation between the predicted behavior and test results. Experimental observations have suggested that the knee points in the DLDR (for example K and K' in Fig.3a) should be located, in comparison with the original proposal [6]:

(i) closer to the 45° - line IJ and

(ii) closer to the 45° - line AB.

On the basis of the DLDR concept, an attempt has been made to obtain experimental curves with a reasonably good overall fit with the present data. One of the characteristics of these curves is that the knee points are all located on the 45^{o}- line IJ, as shown in Fig.4(a), (b) and (c). With these experimental curves, it is found that:

(i) a value of parameter a around 0.7 (instead of 0.6) would be more appropriate for strain-controlled data at the temperatures considered;

(ii) coefficient P is dependent upon the test temperature, the ratio between strain levels imposed and the maximum strain.

In view of these considerations, coefficient P may be interpreted as a material parameter which takes into account the interaction effect between strain levels. This interaction has been discussed extensively in the study of cumulative fatigue damage under stress-controlled conditions [1, 2].

4.3 Relations for coefficient P

In the following developments for coefficient P, exponent a is assumed to be equal to 0.7.

(i) The parameter taking into consideration the temperature effect is defined by the relation:

$$Y = \left(\frac{T_m - T}{T_m - 20}\right)^{1/8} \qquad (5)$$

where T_m and T are the melting and test temperatures in ^{o}C. This parameter has been incorporated in the relation used for determining the reference strain range which may be considered as the endurance strain limit in fatigue cycling [10].

(ii) For the relative difference between strain levels, parameter X is defined as follows:

$$X = \frac{1+\ell n(\Delta\varepsilon_{max}/\Delta\varepsilon_r)}{1+\ell n(\Delta\varepsilon_{min}/\Delta\varepsilon_r)} \qquad (6)$$

in which:

$$\Delta\varepsilon_r = 0.72\,\frac{\sigma_u}{E}\left(\frac{T_m - T}{T_m - 20}\right)^{1/8}$$

where σ_u: ultimate tensile strength is a short-term tensile test

E : elastic modulus

$\Delta\varepsilon_{max}$, $\Delta\varepsilon_{min}$: maximum and minimum values of the two strain range levels used in cumulative damage tests.

The values of σ_u and E should be obtained from a short-term tensile test at the strain rate and the temperature of the fatigue test. The relation for the reference strain range $\Delta\varepsilon_r$ has been discussed elsewhere [11].

(iii) In order to take the maximum strain level into consideration , parameter Z is defined as follows:

$$Z = \ell n\ (2\varepsilon_n/\Delta\varepsilon_{max}) \qquad (7)$$

where ε_n is the total strain corresponding to necking under a short-term tensile test.

In a tensile test, as necking occurs at the onset of plastic instability due to the maximum load, the total strain ε_n is numerically equal to the strain hardening exponent [12]. This exponent has been considered as a reliable parameter for life prediction in high temperature low-cycle fatigue [13].

(iv) On the basis of the experimental curves given in Fig.4, coefficient P is calculated; then the plot of P*, defined as:

$$P^* = \frac{P}{YZ} \qquad (8)$$

in terms of X, as presented in Fig.5, suggests the following relation:

$$P^* = 0.51 + 0.51X \qquad (9)$$

It should be noted that relation (9) has been established on the basis of a limited number of test results on one material. Additional data would, of course, be desirable.

CONCLUSION

An extension of the double linear cumulative damage rule (DLDR) has been made for predicting the cumulative damage effect under strain-controlled fatigue at high temperatures. With results obtained from two-strain level tests, it has been found that the concept is still valid since it takes into consideration the order effect of strain applications.

One of the two parameters involved in the DLDR, which had originally been proposed as a fixed value for most materials at room temperature,has been considered to be dependent upon several factors, namely the difference between strain levels, the test temperature and the maximum strain imposed. In order to have a better correlation between predictions and data, new relations have been developped to evaluate these parameters, on the basis of a limited number of test results on 304 stainless steel under strain-controlled cumulative fatigue at room temperature, 537^o and 650^{o}C.

The essential purpose of the present work was to refine a method which had already been proposed for strain-controlled cumulative damage. It is expected that data on other materials could be incorporated into an approach similar to that described here. This will be discussed in a future paper.

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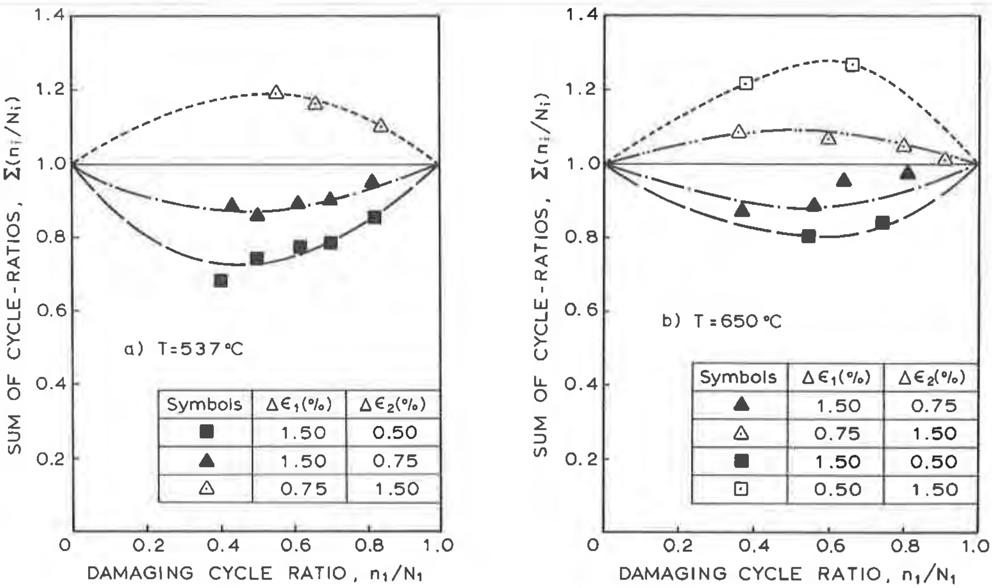


Fig.1 Effect of the order of loading in strain-controlled fatigue at high temperature.

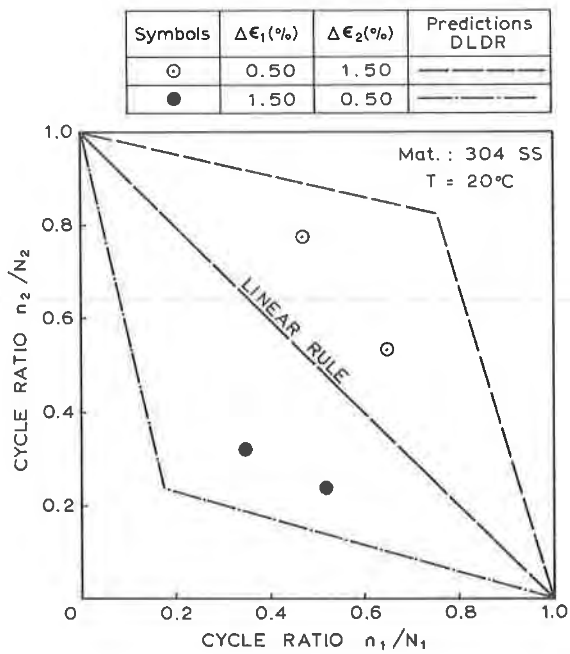


Fig.2 Predictions of the remaining life at the second strain level at room temperature, according to the DLDR.

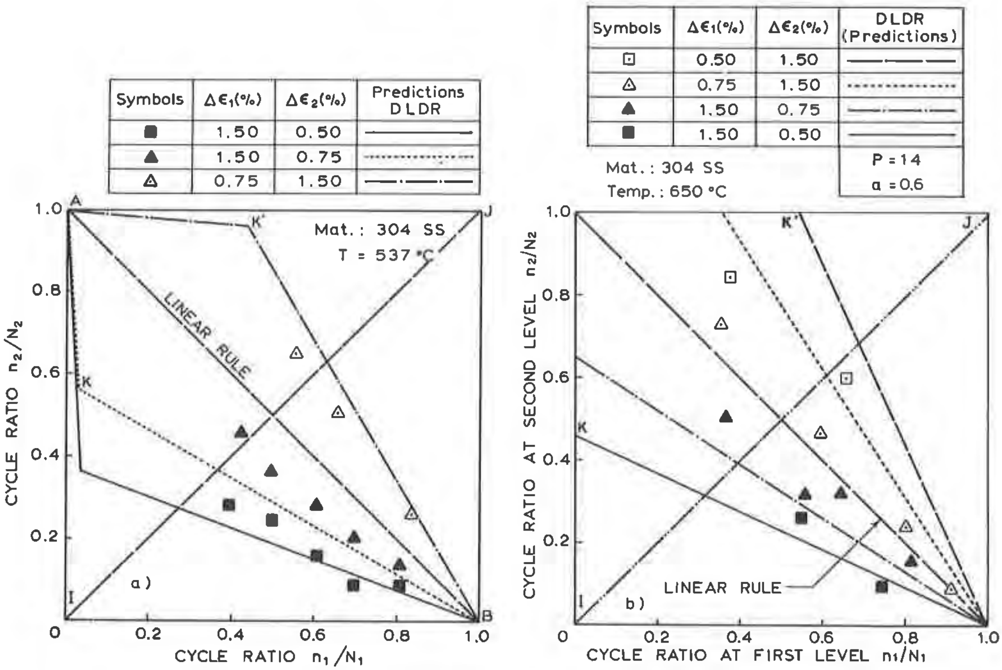
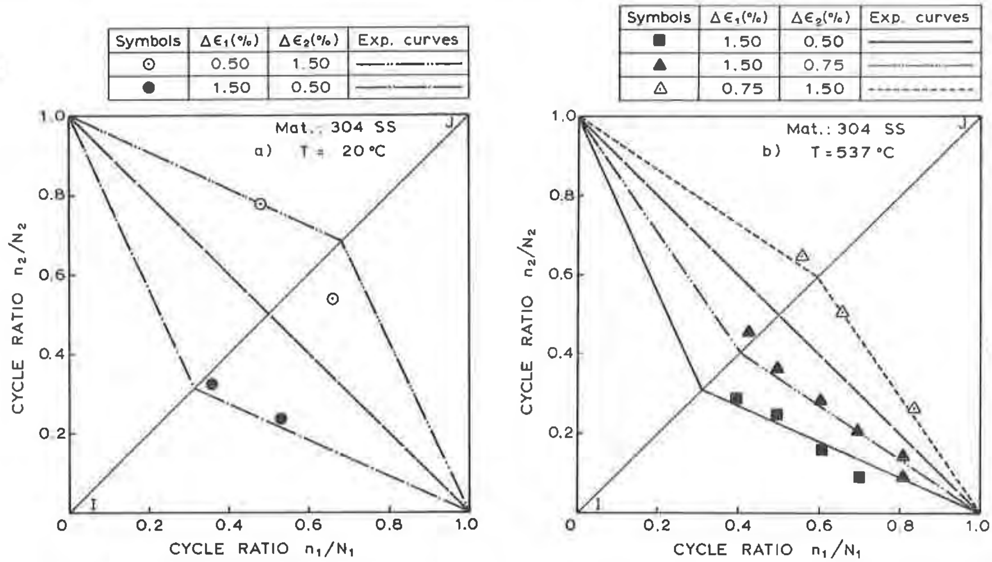


Fig.3 Extension of the DLDR for predicting cumulative damage effect at high temperature.



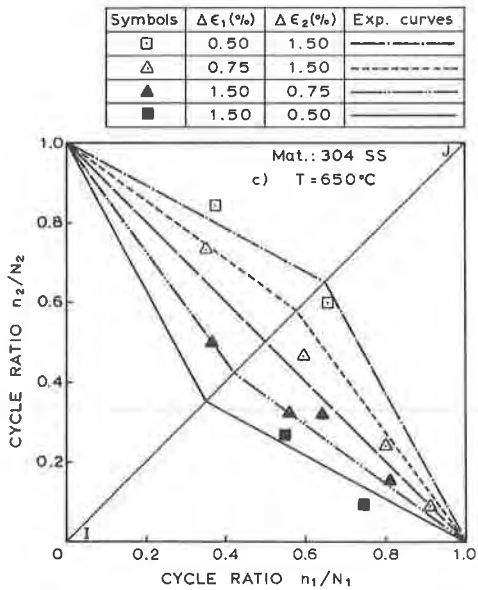


Fig.4 Experimental curves established by using the concept of DLDR.

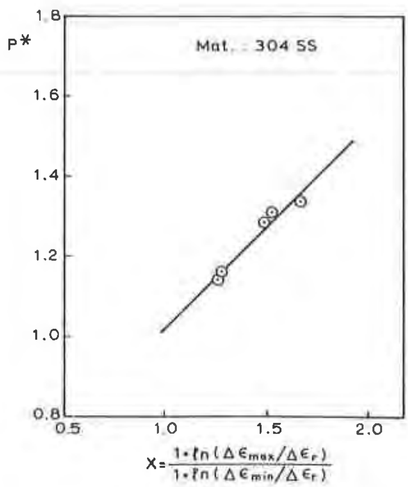


Fig.5 Correlation of parameter P* in terms of parameter X.