Application of the Overstress Concept for Creep–Fatigue Damage Evaluation of 2.25Cr–1Mo Steel

Tai Asayama  
Power Reactor & Nuclear Fuel Development Corporation, Ibaragi, Japan  
Yasuhide Asada  
University of Tokyo, Tokyo, Japan

1. Introduction

A great part of the difficulties encountered in creep–fatigue damage evaluation is caused from the fact that usual creep–fatigue test data include a particular effect of air environment which is superposing upon the creep–fatigue interaction of the material (Coffin, 1973). In order to eliminate the environmental effect, the authors have conducted a series of creep–fatigue tests with 2.25Cr–1Mo steel in a very high vacuum environment of 0.1 μPa (Asayama et al., 1987, 1988, Cheng et al., 1988). It was shown that the results in this high vacuum could be considered to reflect the "pure" creep–fatigue behavior of the material, by which term the authors mean the creep–fatigue behavior completely free from the environmental effect.

The authors analyzed the pure creep–fatigue behavior of the steel based on the overstress concept where the overstress is defined by a difference between an externally applied stress and an internal stress. The overstress is considered as a part of a stress which directly contributes to an inelastic deformation of a material. The internal stress is defined as a part of a stress which represents a resistance of a material to an inelastic deformation.

On the basis of the above examination, a method of creep–fatigue damage evaluation of 2.25Cr–1Mo steel was developed. In the procedure, the role of the overstress and the internal stress of this material were made clear phenomenologically. It was shown that the overstress controls the time–independent part of the creep–fatigue damage and the internal stress controls the time–dependent part. It was shown life prediction was possible within an accuracy of factor of 2.

2. The pure creep–fatigue behavior of 2.25Cr–1Mo steel

A series of creep–fatigue tests were conducted with 2.25Cr–1Mo steel in a very high vacuum of 0.1 μPa at 550°C to eliminate the environmental effect of air. No indications of oxidation or other environmental effects were observed on the external surface or in the internal bulk of the specimens through macroscopic observation or SEM observation. The authors concluded that the results obtained in the above environment can be considered to reflect the pure creep–fatigue behavior of this material at the temperature. The experiments were conducted with a variety of strain wave forms. The waveforms include symmetric continuous cycles, unsymmetric continuous cycles of slow–fast and fast–slow and tension or compression hold cycles. The strain rate ranges from 10^{-5} s^{-1} to 10^{-3}. The result is shown in fig. 1. The conclusions obtained are as follows.

1) Time–dependent life reduction was observed even in this high vacuum environment which is completely free from the air environment. This life reduction was
observed only in such waveforms as a tension going time exceeds a compression going time.

2) Time-independent life reduction was observed in such waveforms as a compression going time exceeds a tension going time. This life reduction is not as significant in the magnitude as the time-dependent life reduction and considered to be caused by a positive mean stress which developed only in these waveforms.

3) A very particular failure behavior was observed. When a time-dependent life reduction occurred, the fracture mode was intergranular. Otherwise, the fracture mode was transgranular.

![Figure 1 Result of Creep-Fatigue Tests](image1)

![Figure 2 Schematic Illustration of Unloading Part of Stress-Strain Curve](image2)

3. Analysis of the Overstress

3.1 Experimental Determination of the Overstress

The creep-fatigue test results obtained in the previous section was analysed based on the overstress concept. An experimental determination of the overstress was made through an analysis of the unloading part of a stress-strain curves. A schematic illustration of the unloading part of the stress-strain curve is shown in Fig. 2. The unloading curve shows a bowing out shape to a direction of an acting stress at the very beginning of unloading. This implies an increase of an inelastic strain just after unloading starts, although the increment is very small. Then a linear part is observed, in which the gradient is equal to the value of Modulus of Elasticity at the temperature. After then a decrease of an inelastic strain is observed against a direction of the stress acting at the start of unloading.

The authors considered that the linear part is an elastic core in which the material behaves as a completely elastic body and that a radius of this part is to be a drag stress D at the peak of the stress-strain curve as indicated in Fig. 2. Moreover, the authors defined that a value of a back stress R at the peak is shown by a value of a stress corresponding to a center of this part. A total value of the internal stress is given by a summation of R and D.

The authors defined a value of the overstress by the following equation, that is, the overstress is given by a difference of the externally applied stress and the internal stress.

\[ \sigma_e = \sigma - (R + D) \]  

(1)
This method is similar to the strain dip test (Alquist, 1969) which has been used to determine a value of an internal stress experimentally. Very important to notice in this kind of method is the relaxation of the internal stress during a measurement, which causes a grater value of the experimentally determined value of the overstress at the peak than the real value of at the peak (Asayama et al. 1987).

2.2 Behavior of the Overstress

The relationship between the overstress determined by the above method and the inelastic strain rate just prior to an unloading was investigated and the result is shown in Fig. 3 by open symbols. It is clear that in the case of this material, the overstress takes a constant value irrespective of the inelastic strain rate. The authors considered that the overstress of this material is strain-rate dependent, which is a very particular observation. The authors furthermore investigated the relationship between the internal stress and the inelastic strain rate. Closed symbols in Fig. 3 shows the result. The grater the inelastic strain rate, the grater the value of the internal stress. That is, the internal stress shows a strain-rate dependency, in the case of 2.25Cr-1Mo steel.

In short, the strain-rate dependency of the stress-strain response is controll-ed by the internal stress, which observation is very particular to this material.

Figure 3 Behavior of Overstress and Internal Stress

4. Creep-fatigue Damage Analysis

4.1 Procedure of Damage Analysis

The overstress has been successfully applied by the authors to the damage evaluation of creep-fatigue interaction of 304 steel (Morishita et al., 1984, 1985, 1988). Here we describe the procedure of the damage analysis. First, the damage which develop during creep-fatigue loading is assumed to be consisted of two parts, that is, time-independent part and time-dependent part. Time-independent damage is developed in all the waveforms while time-dependent damage is developed only in such waveforms as a tension going time exceeds a compression going one. The latter waveforms showed time-dependent life reduction. It is further assumed that both parts of the damage is described in terms of the overstress. The definitions of time-independent damage and time-dependent damage is as follows.

\[
D_I = \int \text{cycle} \sigma e d \varepsilon p
\]

(2)

\[
D_D = \int \text{cycle} \sigma e d t
\]

(3)
$D_I$ and $D_D$ are an inelastic strain and time integration of the overstress for one cycle, respectively. $D_D$ is imposed following restriction,

$$D_D = 0$$

(4)

if equation (3) gives a negative value. Equation (4) restricts an over increase of fatigue life estimation of fast-slow cycles and compression hold cycles, which is contrary to the fact obtained in the experiment.

$D_I$ and $D_D$ are empirically shown to have a correlation with the following life fractions. That is, relations expressed in the following equations are hold.

$$1/N_{f0} = c_1 D_I^{n1}$$

(5)

$$1/N_f - 1/N_{f0} = c_2 D_D^{n2}$$

(6)

$N_{f0}$ is the fatigue life without a time-dependent life reduction and $N_f$ is the fatigue life with a time-dependent life reduction. A predicted fatigue life is obtained by equations (5) and (6). That is,

$$N_{f, pre} = \left( c_1 D_I^{n1} + c_2 D_D^{n2} \right)^{-1}$$

(7)

The relationships corresponding to equation (5) and (6) are shown in Figs. 4 and 5 by the open symbols respectively. In Fig. 5, an offset of fast-slow cycles and compression hold cycles is observed. In Fig. 6, a very large scatter is observed. The result of life prediction is shown in Fig. 7 by open symbols. The values of constants are listed in Table 1. Although the life prediction is accomplished within an accuracy of factor of 2, a scatter with a specific tendency due to a variation of the waveforms is observed.

![Figure 4](image1.png)  ![Figure 5](image2.png)

**Figure 4** Estimation of Time-independent Damage

**Figure 5** Estimation of Time-dependent Damage

4.2 Extension of the Model

As we have investigated in section 3 in this report, the overstress of this steel shows no strain-rate dependency, while the internal stress shows the strain-rate dependency. Here we made a phenomenological investigation on the role of the overstress and the internal stress in a development of the time-dependent damage and time-independent damage in order to extend the method to 2.25 Cr-1Mo steel. In addition, the role of a meanstressed on a development development of the time-independent damage was also considered.
Regarding the time-independent damage, it was shown that the estimation of $D_I$ is improved by taking account of a meanstress effect. $D_I$ was redefined by the following equation.

$$D_I = \int_{\text{cycle}} \sigma \ e \ d \ e + \int_{\text{cycle}} \sigma_1 \ d \ e$$  \hspace{1cm} (8)$$

The signature of the second term of equation (8) coincides with the signature of the meanstress developed in the waveform. That is, equation (8) implies that a positive meanstress accelerates the accumulation of damage, while a negative meanstress plays an opposite role. Closed symbols in Fig. 5 show the result of the estimation by equation (8). Comparing the open symbols with the closed symbols in Fig. 5, it is obvious that the offset of fastslow and compression hold cycles has diminished by the modification of the definition of the time-independent damage parameter $D_I$, which fact shows the modification was reasonable.

As for the time-dependent damage, it was phenomenologically investigated by which variable the damage is controlled. Based on the fact that the internal stress of this material shows a strain-rate dependency, while the overstress not, the authors calculated $D_D$ as a time integration of the internal stress instead of the overstress. The authors assumed that the variable which gives the best correlation of equation (6) is controlling the development of the time-dependent damage of this material. As a result, the following definition was shown to give the best result.

$$D_D = \int_{\text{cycle}} |R + D| \ 2.4 \ \text{sgn} (R + D) \ dt \hspace{1cm} (9)$$

**Table 1 Values of Constants**

<table>
<thead>
<tr>
<th></th>
<th>$C_1$</th>
<th>$n_1$</th>
<th>$C_2$</th>
<th>$n_2$</th>
</tr>
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<tr>
<td>OLD</td>
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<td>1.81</td>
<td>5.41x10^{-6}</td>
<td>0.918</td>
</tr>
<tr>
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<td>2.27x10^{-4}</td>
<td>1.87</td>
<td>4.03x10^{-12}</td>
<td>1.05</td>
</tr>
</tbody>
</table>

**Figure 6 Result of Life Prediction**

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The value of the power of the internal stress is determined empirically. The restriction of equation (4) still imposed. The result of the estimation of the time-dependent damage is shown in Fig. 6 by closed symbols. The scatter due to the variation of waveforms is significantly reduced. It is quite reasonable to consider that the time-dependent part of the damage of this steel is controlled by the internal stress.

Using the equations (8) and (9), life prediction was performed. The result is shown in Fig. 7 by closed symbols. The trend of the scatter was improved by the above extension. The values of the constants are listed in Table 1.

5. Concluding Remarks

The pure creep-fatigue behavior of 2.25Cr-1Mo steel was shown by a series of creep-fatigue tests conducted in a very high vacuum environment which is completely free from the environmental effect of the air. Even in this environment, a time-dependent life reduction was observed in waveforms whose tension going time exceeds the compressive going one. The overstress was determined from an unloading part of stress-strain curves, which technique is equivalent to the strain dip test. The internal stress of this steel is consisted of drag stress and back stress. The total internal stress is given by a summation of the two.

The overstress of this steel shows no strain-rate dependency, while the internal stress shows a strain-rate dependency, which is a very particular characteristic of this material.

The damage equations were extended and time-dependent damage component was described with the internal stress. Time-independent portion of the damage was described with the overstress as it was previously. The estimation of the time-independent damage was shown to be improved by taking account of the mean stress effect.

It is the conclusion of the present study that the creep-fatigue behavior of 2.25Cr-1Mo steel is controlled by the overstress and the internal stress. The former governs the time-independent part and the latter the time-dependent part of the creep-fatigue damage of this steel.

References