An Evaluation of Creep-fatigue Behavior of 304 Stainless Steel in a Very High Vacuum Environment*

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A series of creep-fatigue tests conducted with 304 stainless steel at 650°C in a very high vacuum environment of 0.1 μ Pa were subjected to evaluation based on damage concept relating to an inelastic deformation behavior of the material.

In the model, a damage is separated into two components of time-dependent and -independent. An inelastic strain is separated into time-dependent and -independent strain parameters. Damage components are related to inelastic strain parameters to give damage rate equations in which material constants are determined from experiments.

Key Words : Fatigue, Material Testing, Creep-Fatigue Interaction, Environmental Effect, Vacuum Environment

1. Introduction

It is well known that a prominent time-dependency is observed in a fatigue behavior of metals and alloys at elevated temperatures. The phenomenon is referred to as "Creep-Fatigue Interaction" in Taira's investigation into the mechanism of its origin. The phenomenon is a great subject of research at present as it sometimes becomes critical in an integrity assessment of elevated temperature structures.

Up until today, almost all creep-fatigue data have been obtained by tests conducted in air. And discussions have been developed that strain rate effect and hold time effect observed in these data are caused by the effect of creep in fatigue cycling. From this point of view, several life prediction methods have been developed⁽¹⁻³⁾.

However, the observations by White⁽⁴⁾ and Coffin⁽⁵⁾ made in vacuum of 1 to 10⁻² mPa suggest that the creep-fatigue behavior in vacuum is characterized by an increased strength with a decreased or even diminished time dependency compared to that in air. It was pointed out that an effect of environment, particularly an oxidation at grain boundaries, is an important mechanism originating the creep-fatigue behavior observed in air.

Coffin⁽⁶⁾ has shown in his further study that a reduction of fatigue strength can be observed even in high vacuum when materials are subjected to asymmetric slow-fast triangular strain wave form. Based on this observation, he claims that the creep-fatigue behavior observed in air should be considered to be a "creep-fatigue-environment interaction".

In the authors' previous report, creep-fatigue data on 304 stainless steel were shown which were almost completely free from the environmental effect. The data were obtained in 0.1 μ Pa vacuum in order to make a qualitative evaluation of an environmental effect on creep-fatigue interaction⁽⁷⁾. It has been known from these data that there still exist a strain wave form effect and a strain hold time effect in this high vacuum, while a strain rate effect has completely vanished.

This paper describes the result of a trial evaluation of the present data with a mechanical consideration on a base that the data show only a pure creep-fatigue interaction free from environment.

2. Summary of the Present Creep-fatigue Tests

Strain controlled creep-fatigue tests were conducted with a solution-annealed 304 stainless steel (JIS SUS304). The tests were carried out using hourglass specimens with a minimum section diameter of 10 mm and a theoretical stress concentration factor of 1.06. Test temperature was 650°C and the environment was vacuum of 0.1 μ Pa. The details of the experimental methods are given in authors' previous paper⁽⁷⁾. In this paper only the test results are briefly summarized, which are necessary for introducing the presently developed mechanical model of a creep-fatigue damage.

Figure 1 gives the strain wave forms

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used in the present tests which are classified into three typical patterns, i.e.,

Figure 1 Strain wave programs used for creep-fatigue test in vacuum at 650°C

symmetric triangular, asymmetric triangular and strain hold wave forms.

Figures 2 to 4 show the results of tests with symmetric triangular and strain hold wave forms, respectively. Broken lines in the figures indicate test data on the same material at 650°C in air for reference⁽⁸⁾. Data from 0.1 mPa vacuum are also given in the figures⁽⁹⁾.

Figure 2 Test results for symmetric continuous cycling

Figure 3 Test results for asymmetric continuous cycling of slow-fast and fast-slow

Figure 4 Test results for strain hold time cycling

Summaries of observations on the present test in 0.1 μPa are given as follows.

- (i) An increase of the fatigue lives from those in air is observed and no strain rate effect is seen as far as the present test condition of strain rate is concerned.
- (ii) No life reduction is observed under fast-slow strain cycling which is composed of a higher strain rate in a tension going part of the cycle than in a compression going part.
- (iii) However the opposite case of slow-fast cycle reduces the fatigue life and there is observed a lower fatigue life with a lower strain rate in tension going part.
- (iv) A reduction of fatigue life due to a tensile strain hold time is still observed in high vacuum.
- (v) A recovery is seen in a case where hold time is imposed both at tensile and compressive peak strains. In this case the degree of life reduction is lower than in the case of the hold time only at tensile peak strain.
- (vi) An additional life reduction is observed with a tensile strain hold time imposed upon a slow-fast cycling.
- (vii) The feature of the life reduction is somewhat different between the slow-fast cycling and the tensile strain hold cycling. The former shows an almost uniform reduction of life with respect to strain range, while the amount of life reduction is larger at low strain range in the latter.

The above summaries of the present observations from 0.1 μPa vacuum tests have led the authors to the following conclusion on the pure creep-fatigue interaction in high vacuum environment. That is, a strain wave form in which a time for tension surpasses that of compression makes the fatigue life reduced with respect to the symmetric triangular strain loading with a relatively high strain rate. All of the other strain wave forms do not make the fatigue life reduced.

Examinations of SEM fractographs of the present tests show a good correspondence

with the test results with regard to an occurrence of the fatigue life reduction, that is, transgranular crackings dominate in specimens with no life reduction, while intergranular crackings do in specimens with life reduction. Typical examples of SEM observations of both cases are given in Figures 5 and 6. The authors consider that the above observations coincide with those reported by other investigators.

Figure 5 A typical SEM fractograph for transgranular fracture surface; symmetric continuous cycling, $\dot{\epsilon}_t = 1 \times 10^{-3} \text{ sec}^{-1}$ $\epsilon_{tr} = 1\%$

Figure 6 A typical SEM fractograph for intergranular fracture surface; strain hold-time of 10 minutes at peak tensile strain, $\dot{\epsilon}_t = 1 \times 10^{-3} \text{ sec}^{-1}$ $\epsilon_{tr} = 1\%$

3. Trial Evaluation of Creep-Fatigue Interaction Based on a Damage Concept

The authors consider that a qualitative interpretation can be made of the previously summarized results of high vacuum tests if we assume that an accumulation of time-dependent damage occurs at low inelastic strain rate under superposition of a tensile stress which is not recovered out during following compressive loading, and that the accumulation of this damage reduces a fatigue life. The following damage model has been developed for a trial evaluation of the present results based on this interpretation.

The present damage model is one of the extension of the damage separation concept tentatively proposed by one of the authors⁽⁹⁾ in which an inelastic strain range is separated into two parts, time-independent and -dependent, and related to damage components, time-independent and -dependent, respectively. In the present extension, an incremental form of the damage growth law is developed in terms of parameters representing an inelastic strain at an arbitrary instant of loading but not its range.

As it is well observed, a decrease in strain rate causes a reduction of stress as schematically shown in Figure 7(a). The time-dependent inelastic strain parameter at an arbitrary instant of strain cycling is defined by ϵ_{pd} indicated in Figure 7(b). Here ϵ_{pd} is given by a difference of a strain between the stress-strain curve obtained under a strain rate of 10^{-3} sec^{-1} and the one with a different strain rate at the same stress where the latter curve is shifted to the right or left to coincide with the former on the strain axis (abscissa). In Figure 7(b), an example is shown for the determination of ϵ_{pd} in tension going part of the cycle but the method is the same as in the compression part.

Figure 7 A schematic illustration for the definition of time-dependent inelastic strain parameter ϵ_{pd}

The present method assumes that the strain rate dependence of a stress-strain relation is fully saturated at a strain rate of 10^{-3} sec^{-1} which serves the basis of the analysis. This implies that the stress-strain response at this particular strain rate does not include a time-dependency anymore. Authors consider that this assumption is adequate from observations on the test results in air although the test condition in the vacuum is not wide enough to confirm this.

Figures 8 and 9 show examples of an evolution of ϵ_{pd} during a tensile loading part of a cycle where abscissa of the figures mean a total strain ϵ_t subtracted by a value of the total strain ϵ_t^* at which a significant amount of ϵ_{pd} begins to be generated. As shown in these two figures, a quasi-linear relationship holds between

EPD and $\epsilon_t - \epsilon_t^*$ regardless of strain range. Another definition of the time-dependent inelastic strain parameter is necessary for relaxation during a hold time. ϵ_{PD} during a hold time is defined by a held strain subtracted by the strain of the reference 10^{-3}sec^{-1} strain rate curve at the same stress where these two loading

Figure 8 An example of the evolution of time dependent inelastic strain parameter during tensile loading portion; slow-fast cycling, $\dot{\epsilon}_t = 1 \times 10^{-4} \text{sec}^{-1}$

Figure 9 An example of the evolution of time-dependent inelastic strain parameter during tensile loading portion; slow-fast cycling, $\dot{\epsilon}_{t1}/\dot{\epsilon}_{tu} = 1 \times 10^{-5} / 1 \times 10^{-3} \text{sec}^{-1}$

Figure 10 An example of the evolution of time-dependent inelastic strain parameter during hold-time portion; hold time of 10 minutes at a peak tensile strain $\dot{\epsilon}_t = 1 \times 10^{-3} 1/S$

curves coincide on the abscissa, again. Figure 10 shows an example of the evolution of ϵ_{PD} during a strain hold time.

The time-dependent strain parameter ϵ_{PD} defined above does not have a direct physical meaning as strain itself, but this definition was adopted by analogy from the usage that an excessive strain due to a lowered strain rate in the cyclic stress strain relation is regarded as creep strain.

Next assumed is the following damage evolution model incorporating the time-independent and -dependent inelastic strain parameters ϵ_{PI} and ϵ_{PD} . The basic concept of the model lies in the assumption that a failure occurs when a linear summation of a time-dependent damage and -dependent damage reaches a critical value. The concept is fundamentally the same as that of Creep-Fatigue Interaction. The evaluation equations of the damages are given by Eqs. (1) and (2) with an additional restriction given by Eq. (3).

$$\frac{1}{\phi_I} \frac{d\phi_I}{dn} = G(\Delta\epsilon_{PI})^\alpha \quad (1)$$

$$\frac{1}{\phi_D} \frac{d\phi_D}{dt} = B \left| \frac{d\epsilon_{PD}}{dt} \right|^m |\sigma|^n \text{sgn}(\sigma) \quad (2)$$

$$\phi_D \geq 0 \quad (3)$$

where ϕ_I and ϕ_D are the time-independent damage and -dependent damage components, respectively. And $\Delta\epsilon_{PI}$ is a range of time-independent strains given by an inelastic strain range with 10^{-3}sec^{-1} strain rate cycles. And n means a number of strain cycles, t means time and G , B , m , α and β are material constants.

Here assumed is a similar type formulae to the damage rate equation proposed by Majumdar⁽¹⁰⁾. The restriction by Eq. (3) is also necessary to adjust the model to the experimental observation that ϕ_D increases during a tension going part and decreases during compression, but it is always positive or zero.

The evolution equation of a time-independent damage given by Eq. (1) is integrated from $n=0$ to N_f to give Eq. (4) which can be transformed into the same form as the well known Coffin-Manson equation through a simple rewriting of coefficients.

$$N_f = C(\Delta\epsilon_{PI})^{-\alpha} \quad (4)$$

where,

$$C = \frac{1}{G} \ln(\phi_{I1}/\phi_{I0}) \quad (5)$$

where; ϕ_{I0} and ϕ_{I1} being the values of ϕ_I at the initial and failure states.

Coefficients α and C in Eq. (4) can be determined from the fatigue test results with a strain rate of 10^{-3}sec^{-1} as we assume that ϵ_{PD} does not generate in a symmetric triangular strain wave form with

that particular strain rate. In the present case $C=0.67$ and $\alpha=1.9$.

Eq. (2), and evolution equation of a time-dependent damage, are integrated for one cycle of loading and unloading to give Eq. (6).

$$\ln\left(\frac{\phi_{D3}}{\phi_{D1}}\right) = B \left[\int_1^2 \left| \frac{d\epsilon_{PD}}{dt} \right|^\beta |\sigma|^\alpha dt - \int_2^3 \left| \frac{d\epsilon_{PD}}{dt} \right|^\beta |\sigma|^\alpha dt \right] \quad (6)$$

where the numerical numbers 1, 2 and 3 indicate the upper and lower points of the integration which correspond to the compressive peak, tensile peak and the next compressive peak forming one cycle of a stress-strain hysteresis loop. Following approximation was made with respect to stress-strain response to determine the coefficients β and α . The stress changes itself rapidly just after a loading reversal and reaches quickly the peak value of $\sigma_{\max}$ in tension or $\sigma_{\min}$ in compression. This observation leads us to the assumption that the flow stress in cyclic loading is held constant at $\sigma_{\max}$ during tension and at $\sigma_{\min}$ at compression. The value of stress during a strain hold time is assumed to be equal to a constant value of $\sigma_{\max}'$ or $\sigma_{\min}'$ for a tensile hold and compressive hold respectively, as observations show that the stress relaxation occurs initially at a high rate and continues at a very slow rate. This assumption transforms Eq. (6) into Eq. (7).

$$\ln\left(\frac{\phi_{D3}}{\phi_{D1}}\right) = \begin{cases} B \left[|\sigma_t^*|^\alpha \int_0^{\tau_t} \left| \frac{d\epsilon_{PD}}{dt} \right|^\beta dt - |\sigma_c^*|^\alpha \int_0^{\tau_c} \left| \frac{d\epsilon_{PD}}{dt} \right|^\beta dt \right] & (\tau_t > \tau_c) \\ 0 & (\tau_t \leq \tau_c) \end{cases} \quad (7)$$

where, σ_t^* is equal to $\sigma_{\max}$ and to $\sigma_{\max}'$ for tension loading and for tensile strain hold, respectively, and σ_c^* is equal to $\sigma_{\min}$ and $\sigma_{\min}'$ for compression loading and compressive strain hold, respectively. τ_t and τ_c are the time for tension going and compression going, respectively. In the present case, the second term of the right hand side of Eq. (7) is dropped as τ_t is always larger than τ_c . By assuming β is equal to unity, Eq. (7) is rewritten as Eq. (8).

$$\ln\left(\frac{\phi_{D3}}{\phi_{D1}}\right) = \begin{cases} B \epsilon_{PD} |\sigma_t^*|^\alpha & (\tau_t > \tau_c) \\ 0 & (\tau_t \leq \tau_c) \end{cases} \quad (8)$$

Eq. (8) is compared with experiments on further assumption of m to be zero. Figure 11 shows a correlation between ϵ_{PD} and an experimentally obtained time-dependent damage per cycle ϕ_D expressed by Eq. (9),

$$\phi_D = \frac{1}{N_f} - \frac{1}{N_{f0}} \quad (9)$$

where N_{f0} means the fatigue life in case of no life reduction. The figure is obtained from slow-fast cycle tests. As shown in the figure, there was observed a reasonable linear relationship between two parameters in log-log plot and the gradient of the line is equal to 1.1 which is very close to unity. This result implies that the assumption of $\beta=1$ is reasonable.

Figure 11 Relation between time-dependent damage ϕ_D and time-dependent inelastic strain parameter ϵ_{PD} , for slow-fast cycle

An exact method for determining the value of m is to investigate the relation between m and σ^* . However in the present analysis m is assumed to be unity in order to eliminate an experimental error, as $\sigma_{\max}$ or $\sigma_{\max}'$ is not so sensitive to a strain rate or strain range. Figure 12 shows the correlation between Eq. (9) and experimental results with slow-fast and 10 min. tensile hold strain cycling. The figure shows a reasonable correspondence existing between these two parameters.

Figure 12 Correlation between the time-dependent damage and the product of the time-dependent inelastic strain parameter and the representative stress

The observation on Figures 11 and 12 enables us to assume both β and m are equal to unity. With these quantitative assumptions, the present damage model is summarized as follows, where coefficients G and α are referred previously and β is equal to 0.11.

$$\frac{1}{\phi_i} \frac{d\phi_i}{dn} = G(\Delta\epsilon_{PI})^\alpha \dots\dots\dots(10)$$

$$\frac{1}{\phi_D} \frac{d\phi_D}{dt} = B \left| \frac{d\epsilon_{PD}}{dt} \right| |\sigma^*| \text{sgn}(\sigma) \dots\dots\dots(11)$$

$$\phi_D \geq 0 \dots\dots\dots(12)$$

4. Conclusions

A trial evaluation has been made using mechanical quantities which relate an inelastic deformation with creep-fatigue test results obtained with SUS304 steel in high vacuum of 0.1 μ Pa in which the environmental effect is almost completely eliminated.

The present study is summarized as follows.

(1) Inelastic strain parameters, ϵ_{PI} and ϵ_{PD} , have been introduced to separate an inelastic strain into time-independent and -dependent parts. The authors consider that ϵ_{PI} is represented by an inelastic strain observed in a saturated stress-strain loop obtained under a strain rate of 10^{-3}sec^{-1} at which a time-dependent inelastic deformation behavior is almost non-existent. The authors define ϵ_{PD} as an additional inelastic strain to that of a reference stress-strain relation for a loading part and as a difference of inelastic strain between the held strain and a strain of the reference stress-strain curve, where the reference curve is obtained under strain cycling with 10^{-3}sec^{-1} strain rate.

(2) A reasonable linear correlation is observed between ϵ_{PD} and $\epsilon_t - \epsilon_t^*$, where ϵ_t^* means the strain at which a significant amount of ϵ_{PD} begins to be generated. This relation is independent of a strain wave form and a strain range but dependent on a strain rate.

(3) The experimental results are subjected to analysis based on a damage concept where a damage is separated into a time-independent part ϕ_I and -dependent part ϕ_D . Empirical formulation is given to describe an evolution law of damages in terms of ϵ_{PI} and ϵ_{PD} . In the formulation, coefficients β and m are temporarily quantified.

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