Effect of Nonproportional Loading on Creep-Fatigue Properties of 304 Stainless Steel at Low Strain Ranges near Elastic Region

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ABSTRACT

Effect of nonproportional strain path on fatigue / creep-fatigue properties was investigated with 304 stainless steel at 550°C under strain controlled biaxial conditions. The effect of nonproportional strain path on fatigue / creep-fatigue strength was observed at the lowest strain range investigated, that is, 0.2% for fatigue loading and 0.5% for creep-fatigue loading. The Mises type path dependent equivalent strain range was employed instead of ASME type equivalent strain range to evaluate the fatigue / creep-fatigue test results on the basis of the uniaxial material properties which have been extensively accumulated. Fatigue damage and creep damage were calculated based on the linear damage summation rule. The life prediction was possible within an accuracy of factor of 2.

1 INTRODUCTION

From the viewpoint of the improvement of creep-fatigue damage evaluation methods in the structural design codes, damage assessment under multiaxial loading conditions is one of the most important problems. Although the material behavior under multiaxial loading conditions is rather complicated compared with that under uniaxial loading, the damage assessment procedure is required to be as simple as possible and have enough experimental basis. From this standpoint, uniaxialization of strain histories of structural components under multiaxial loading, which enables the evaluation of material strength under multiaxial conditions on the basis of uniaxial material strength, is proposed (Sakon et al, 1987). Based on this concept, a multiaxial creep-fatigue damage assessment method which utilizes the uniaxial material properties extensively accumulated is being developed in Power Reactor and Nuclear Fuel Development Corporation (Asayama et al, 1989a, Asayama et al, 1989b, Asayama et al, 1991).

The method deals with the problem of the underestimation of fatigue damage under nonproportional loading. It is widely known that considerable life reduction and the additional strain hardening occur under nonproportional combined loading (Krempel et al, 1984, Benallal et al, 1987). But most of the studies reported so far have dealt with fatigue properties at relatively higher strain ranges and few studies have been reported concerning the fatigue properties at low strain ranges and creep-fatigue properties which have practical importance.

The objectives of this paper are to provide observations concerning the fatigue / creep-fatigue strength of SUS304 stainless steel under biaxial loading at relatively low strain ranges near elastic region and to propose a creep-fatigue damage assessment method based on the experimental results. The minimum strain range employed for nonproportional loading was 0.2 % for fatigue tests and 0.5 % for creep-fatigue tests. The fatigue life reduction and the additional strain hardening due to the nonproportional loading are discussed.

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tionality of strain path imposed was examined and an equivalent strain range was employed for the uniaxialization of strain history. Based on this equivalent strain range, fatigue damage and creep damage were evaluated and the effect of nonproportional strain path on fatigue damage and creep damage were discussed. Life prediction of test results were conducted on the basis of linear damage summation rule utilizing the material properties under uniaxial conditions which have been extensively accumulated in PNC.

2 EXPERIMENTAL PROCEDURE

2.1 Material and test specimen

The material used in the present study was SUS304 stainless steel from a hot rolled plate (1000 x 1000 x 40 mm) and was used in the solution annealed condition (1100 °C x 48 min). The chemical composition and the mechanical properties at room temperature are shown in table 1. Hollow cylinder specimens of 30mm parallel gauge length with 22 and 15 mm outside and inside diameters respectively were machined after the heat treatment. Configuration of the specimen is shown in Fig. 1.

Table 1 Chemical composition and mechanical properties of the tested material

1100°C X 48min WQ											wt %
C	Si	Mn	P	S	Ni	Cr	Mo	Ti	Al	N	Nb + Ta
0.050	0.60	0.87	0.026	0.002	8.94	18.59	0.11	< 0.002	0.013	0.019	< 0.003

Yield Strength MPa	Tensile Strength MPa	Elongation %
213.6	623.3	71.9

Fig. 1 Test specimen

2.2 Test facility and test conditions

A hydro-servo axial-torsional fatigue test machine was utilized. The fatigue and creep-fatigue tests were conducted under strain controlled condition at 550 °C in air environment. Axial strain and torsional strain were controlled and measured independently. Triangular waveform and sinusoidal waveform were employed. Loading condition included uniaxial loading, pure torsional loading, combined proportional loading and nonproportional loading. For combined loadings, a biaxiality factor was defined by $\lambda = \Delta \gamma / \Delta \varepsilon$ with λ taking a value of 1.7. For nonproportional loading, a phase angle of 90 degrees was introduced. For all of those loading conditions, fatigue tests (no

strain hold period is imposed) and creep-fatigue tests (a strain hold period is imposed) were conducted. For creep-fatigue tests, strain hold period of 1 hour was imposed at a tensile peak of axial strain except pure torsional loading, considering the fact that under uniaxial loading condition the most significant life reduction is observed when a strain hold period is imposed at a tensile strain peak. For pure torsional loading, a strain hold period of 1 hour was imposed at an extreme value of torsional strain. For combined proportional and nonproportional loadings, both axial strain and torsional strain were held simultaneously. The loading conditions are summarized in Table 2. The strain rate at loading / unloading portion was a nominal value of 0.1 %/sec which was defined by $\Delta \epsilon_{eq} / \tau$, where $\Delta \epsilon_{eq}$ and τ are ASME type equivalent strain range (see 3.1 in this paper) and cycle time respectively.

Failure was defined as a 25 percent fall in load range below the stabilized cyclic hardening curve.

Table 2 List of waveforms

3 RESULTS OF EXPERIMENT

3.1 Stress-strain behavior under biaxial conditions

ASME type equivalent strain range $\Delta \epsilon_{eq}$ and Mises equivalent stress range $\Delta \sigma_{eq}$ are widely used in evaluation of stress-strain response under multiaxial conditions. Those

are defined by the following equations.

$$\Delta \varepsilon_{eq} = \left(\Delta \varepsilon^2 + \Delta \gamma^2 / 3 \right)^{1/2} \quad (1)$$

$$\Delta \sigma_{eq} = \left(\Delta \sigma^2 + 3 \Delta \tau^2 \right)^{1/2} \quad (2)$$

Where $\Delta \varepsilon$, $\Delta \gamma$, $\Delta \sigma$, $\Delta \tau$ are axial strain, torsional strain, axial stress and torsional stress, respectively. Figure 2 shows the Mises equivalent stress range obtained in the present study as a function of ASME type equivalent strain range. It is observed from Fig.2 that the additional strain hardening due to the nonproportionality of the strain path (Krempf et al, 1984, Marquis et al, 1987) is obviously observed in the present study. About 30 % increase of Mises equivalent strain range is observed for nonproportional fatigue loading compared with uniaxial loading. But the amount of increase was less at lower strain ranges near elastic region and it was about 15 % at a strain range of 0.2%. Almost the same amount of increase in Mises equivalent stress range was observed for nonproportional creep-fatigue loading.

For proportional loadings, the pure torsional fatigue / creep-fatigue loading showed somewhat lower stress range compared with uniaxial loading and combined proportional loadings.

In order to estimate the additional strain hardening observed for nonproportional loadings, the Mises type equivalent strain range $\Delta \varepsilon_{pth}$, which takes into account the strain path imposed was employed (Sakon, T. et al, 1987). $\Delta \varepsilon_{pth}$ is defined as follows.

$$\Delta \varepsilon_{pth} = \int d\varepsilon_{eq} \quad (3)$$

Fig. 2 Stress-strain response represented by the ASME type equivalent strain range

Fig. 3 Stress-strain response represented by the Mises type path dependent equivalent strain range

where $d\epsilon$ is an increment of Mises type equivalent strain. Integration is conducted between the two points in a strain cycle where axial strain take extreme values. In Equation (3), $\Delta \epsilon_{pth}$ is calculated based on total strain instead of plastic strain which is used in the original Mises equivalent strain range. The relationship between the Mises type path dependent equivalent strain range $\Delta \epsilon_{pth}$ and Mises equivalent stress range $\Delta \sigma_{eq}$ is shown in Fig.3. It is observed that the estimation was improved by the Mises type path dependent equivalent strain range $\Delta \epsilon_{pth}$, although the estimation of the additional hardening is not enough.

3.2 Stress relaxation behavior under biaxial conditions

It is reported that under certain multiaxial conditions, the amount of stress relaxation is reduced compared with that under uniaxial conditions provided that the initial stress of stress relaxation is the same (Severud et al, 1987, Severud, 1989). The amount of stress relaxation obtained in the present study is plotted as a function of the initial (Mises equivalent) stress of a stress relaxation in Fig. 4. It is known from Fig.4 that the amount of stress relaxation is large in order of uniaxial loading, pure torsional loading, combined proportional loading and nonproportional loading. Therefore it was made clear that the amount of stress relaxation was reduced under axial-torsional biaxial conditions, particularly under nonproportional condition.

Stress path of nonproportional creep-fatigue cycle at the strain range of 1% is shown in Fig.5. It is clearly observed that the stress relaxation occurred proportionally toward the origin of the stress-strain plane just like the combined proportional loading although the stress path at loading / unloading portion was nonproportional. This observation held true irrespective of strain range. And it indicates that the evaluation of stress relaxation under nonproportional loading can be performed by the same method used for proportional loading.

Fig. 4 Amount of stress relaxation under nonproportional loading

3.3 Fatigue / creep-fatigue life under biaxial conditions

The results of biaxial fatigue / creep-fatigue tests are shown in Fig.6. Figure 6 shows the relationship between ASME type strain range $\Delta \epsilon_{eq}$ and number of cycles to failure N_f .

Fatigue life

For proportional loadings, fatigue life was in the order of pure torsional loading, combined proportional loading and uniaxial loading although the difference was small.

Fig. 5 Proportionality of stress relaxation under nonproportional creep-fatigue loading

The fatigue strength of uniaxial loading showed the almost the same strength as the average trend curve determined by various heats of 304 stainless steel (Wada et al, 1987). The nonproportional combined loading showed a considerable life reduction compared with the uniaxial loading. This tendency held true even at a strain range as low as 0.2 %. The amount of life reduction showed no particular dependence on strain range and the fatigue life under nonproportional combined loading was reduced to 1/4-1/20 of that under uniaxial loading.

It was revealed that the effect of nonproportional strain path on fatigue strength of this material still existed at strain range of 0.2%.

Creep-fatigue life

Fig. 6 Result of biaxial fatigue / creep-fatigue tests

Creep-fatigue life showed life reduction compared with fatigue life under the same ASME type strain range for all types of loadings. Creep-fatigue life reduced to 1/3-1/5 of fatigue life. The amount of life reduction was almost the same for all the loading conditions including the nonproportional loading. It was made clear that creep-fatigue life reduction occurs under nonproportional loading conditions just as under proportional loadings.

3.4 SEM observations

For uniaxial loading, a clear relationship has been observed between loading condition and fracture mode for 304 stainless steel (Morishita et al, 1984). That is, transgranular fracture was observed for fatigue loading and intergranular fracture, which indicates the effect of creep, was observed for creep-fatigue loading. In the present study, a series of scanning electron microscope (SEM) observation was made to check if the above observation obtained for uniaxial loading also hold for biaxial loading conditions including nonproportional loading.

Figure 7 shows the result of the SEM observation. Fracture surface under nonproportional fatigue loading (Fig.7d) is similar to that of torsional fatigue loading which showed transgranular fracture mode with rubbing marks (Fig.7b). Striation marks which were observed on the surfaces of uniaxial loading (Fig.7a) and combined proportional loading (Fig.7c) were not observed. For nonproportional creep-fatigue loading (Fig. 7d), the fracture surface is similar to those of uniaxial creep-fatigue loading (Fig. 7a) and combined proportional creep-fatigue loading (Fig.7c), showing a typical intergranular fracture mode.

Therefore it can be concluded that fracture mode was transgranular for fatigue loading and intergranular for creep-fatigue loading under nonproportional loading conditions, which is the same as the case of uniaxial loading. And as far as fracture surface observations concerns, the effect of the nonproportionality of strain path is evident only for fatigue loading and is not observed for creep-fatigue loading. This is probably because the strain hold was imposed at a tensile peak of axial strain when the torsional strain is zero.

Fig. 7a Result of SEM observation (Uniaxial loading)

Fig. 7b Result of SEM observation (Torsional loading)

Fig. 7c Result of SEM observation
(Combined proportional loading)

Fig. 7d Result of SEM observation
(Nonproportional loading)

4 EVALUATION OF TEST RESULTS

4.1 Creep-fatigue evaluation method under uniaxial condition

PNC has developed a creep-fatigue life prediction method on the basis of uniaxial material properties extensively obtained. The method is summarized here (Wada et al, 1987, Aoto et al, 1987, Wada et al, 1986, Yoshitake et al, 1986, Kawasaki et al, 1989).

This method requires the following four properties of the material evaluated.

- (a) Fatigue life vs. strain range.
- (b) Strain range vs. stress range at mid-life.
- (c) Creep strain vs. time.
- (d) Stress vs. creep rupture time.

The procedure is as follows.

(1) Fatigue damage D_f is calculated as a life fraction consumed in the loading procedure as expressed by the following equation.

$$D_f = N/N_f \quad | \quad \Delta \epsilon \quad (4)$$

where N_f is a fatigue life that corresponds to the applied strain range $\Delta \epsilon$ on the average trend curve of fatigue strength settled based on the uniaxial fatigue test results of various heats of 304 stainless steel. N is number of cycles imposed.

(2) Creep damage is calculated as a time fraction consumed during the strain hold periods as expressed by the following equation.

$$D_c = N \int_0^{t_h} dt / tr(\sigma) \quad (5)$$

where $tr(\sigma)$ is uniaxial creep rupture time under stress σ (see(5)). t_h is a strain hold time per one cycle. The integration is conducted for one cycle. Stress relaxation

behavior needed to calculate Equation (5) is determined by the following procedure.

(3) The initial stress at a stress relaxation is obtained as a half of a stress range that corresponds to the applied strain range $\Delta \epsilon$ on the cyclic stress-strain curve at mid-life which is settled based on the experimental results of uniaxial fatigue tests of various heats of 304 stainless steel.

(4) Stress relaxation curve is estimated based on the average trend curve that represents the relationship between time and uniaxial creep strain and the classic strain hardening law.

(5) A rupture time for a given stress is obtained by the average trend curve of stress and rupture time which is settled based on the uniaxial creep test results of various heats of 304 stainless steel.

(6) Creep-fatigue rupture is assumed to obey the Campbell criterion.

4.2 Fatigue damage under biaxial condition

It was proposed in 3.1 that a Mises type strain path dependent equivalent strain range be used for estimation of the additional strain hardening that occurs under nonproportional loading. Based on this, the Mises type path dependent equivalent strain range was used to estimate fatigue damage under biaxial conditions. Fatigue damage under biaxial condition is assumed to be expressed as follows.

$$D_f = N/N_f \quad | \quad \Delta \epsilon_{pth} \quad (6)$$

For proportional loading, ASME type equivalent strain range and Mises type path dependent strain range give the same value. For nonproportional loading, the Mises type path dependent equivalent strain range gives a larger value compared with the ASME type equivalent strain range and the difference between the two is maximum at the phase angle of 90 degrees. In this case, $\Delta \epsilon_{pth}$ equals $\pi/2$ times $\Delta \epsilon_{eq}$.

4.3 Creep damage under biaxial condition

The initial stress of a stress relaxation was calculated as a half of the strain range that corresponds to the Mises type path dependent equivalent strain range obtained by Equation (3). It is to be noted that the initial stress of stress relaxation under nonproportional loading is estimated higher than that under uniaxial loading by Equation (3). It is because the estimation of the additional strain hardening by Equation (3) is not enough as mentioned in 3.1. In the present study, for simplicity, no further discussion was made at this point.

The stress relaxation curve was assumed to be estimated by the relationship between time and creep strain obtained under uniaxial conditions by using the Mises equivalent stress calculated by Equation (2). This assumption was made based on the fact that the stress relaxation under nonproportional loading occurred proportionally as shown in Fig.5.

The amount of stress relaxation depends on type of loading as shown in Fig.4. But in the present study, for simplicity, the difference of the amount of relaxation was not take into account. The relationship between the initial stress and the amount of relaxation estimated by the relationship between creep strain and time obtained under uniaxial condition is shown in Fig.4 by a dashed line. This relationship was used for the evaluation of stress relaxation behavior of both the proportional loading and the nonproportional loading.

The relationship between applied stress and time to failure obtained under uniaxial conditions was used to evaluate the creep damage under biaxial conditions. Creep damage under biaxial conditions was assumed to be estimated by the trend curve by using the Mises equivalent stress σ_{eq} as expressed by the following equation.

$$D_c = N \int \frac{dt}{t_r(\sigma_{eq})} \quad (7)$$

Fig. 8 Creep-fatigue damage assessment based on the method proposed in the present study

4.4 Result of life prediction

The fatigue damage and the creep damage calculated by the above procedure are plotted on the Campbell diagram in Fig.8. It is seen that damage assessment was fairly reasonable except for pure torsional loading which was estimated somewhat conservatively. The result of life prediction based on the damage assessment is shown in Fig.9. For most of the data, life prediction was possible within accuracy of factor of 2. Nonproportional fatigue loading at the lowest strain range investigated and pure torsional creep-fatigue loading were estimated conservatively.

Fig. 9 Result of life prediction

4.5 Estimation of creep damage at low strain ranges near elastic region

From the above observations, it was shown that fatigue / creep-fatigue strength under proportional loading and nonproportional loading was reasonably evaluated by the method proposed in the present study at least for strain ranges above 0.2% for fatigue strength and 0.5% for creep-fatigue strength. In this section we will discuss the creep-fatigue life evaluation for strain ranges below 0.5%.

As stated above, in the method proposed in the present study, the creep damage is calculated based on three properties obtained under uniaxial conditions, that is, the initial stress of stress relaxation, the amount of stress relaxation and the creep strength. In the present study, simplification was made in evaluation of the initial stress and the amount of stress relaxation. Therefore, effect of the simplification made in the present study on the creep-fatigue strength evaluation at lower strain ranges is to be considered.

If we focus on the low strain ranges near elastic region, the difference of the initial stress between experiment and estimation will be minimized. This is because the amount of the additional strain hardening due to nonproportional strain path is very small at low strain ranges as indicated in Fig.3. For the amount of stress relaxation, although it can be inferred from Fig.4 that the amount of stress relaxation is smaller under nonproportional loading even if the initial stress of relaxation is small, the amount of reduction is considered to be reduced at lower strain ranges compared with that at higher strain ranges.

To sum up, the effect of the simplifications made in the present study is considered to be smaller at lower strain ranges and it is implied that the creep-fatigue damage evaluation method proposed in the present study is also valid for lower strain ranges below 0.5% which was not investigated in the present study. A series of creep-fatigue tests are being conducted to confirm this point.

5 CONCLUSIONS

A series of axial-torsional biaxial creep-fatigue tests were performed with 304 stainless steel at 550 °C to check the effect of strain path imposed on the fatigue and creep-fatigue strength under nonproportional loading conditions. The following observations were made.

(1) Fatigue strength under nonproportional loading conditions reduced to 1/4 - 1/20 of that under proportional loading. This tendency was still observed at a low strain range of 0.2% which is very close to elastic region.

(2) Creep-fatigue life under nonproportional loading showed life reduction compared with fatigue under nonproportional loading. The amount of life reduction due to strain hold period was almost the same as the case of proportional loading.

(3) Proportional stress relaxation was observed under nonproportional loading just like under proportional loading.

(4) Transgranular fracture was observed for nonproportional fatigue loading and intergranular fracture was observed for nonproportional creep-fatigue loading. It was the same observation as that made for proportional loading.

(5) Fatigue damage was defined based on the Mises type path dependent equivalent strain range and creep damage was defined based on the Mises equivalent stress. Fatigue damage and creep damage were evaluated based on the uniaxial material properties extensively obtained by PNC.

(6) The result of damage evaluation was fairly reasonable and life prediction was possible for most of the data within an accuracy of factor of 2.

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