

A Study on Strain History Effects to the Creep-Fatigue Strength of 304 Stainless Steel

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ABSTRACT

The stress variation creep test and the strain variation fatigue test were conducted for evaluation of linear damage fractions. Modified damage evaluation procedures were proposed to improve its predictability. The creep-fatigue evaluation method based on linear damage fraction rule could give the proper prediction for creep-fatigue data with several strain history.

1 INTRODUCTION

In this study, several creep, fatigue and creep-fatigue tests for 304 stainless steel were performed to investigate strain history effects to the material strength. Another purpose of this work is to confirm the generality of application of linear damage fraction rule. The creep-fatigue evaluation based on linear damage fraction rule was developed for the structural materials of main LMFBR components (Aoto et al. 1987). The analytical representation method of creep and fatigue properties applied to evaluate damage fractions respectively were developed to give proper estimation for observed results (Wada et al. 1987; Yoshitake et al. 1986). Further, the stress relaxation behavior used to evaluate creep damage could be represented analytically using the creep strain equation with the classical strain hardening theory (Aoto et al. 1986). This paper shows that the creep-fatigue lives included several strain history effects can be predicted by the present creep-fatigue evaluation method.

2 EXPERIMENTAL PROCEDURE

2.1 Material

The material used for this study is a 40 mm thick 304 stainless steel. The chemical compositions is given in Table 1. The steel plate was given a solution treatment (water quench after holding of 48 minutes at 1100 °C), before the machining of specimens. The test specimens of the creep and fatigue tests are

Table 1 Chemical compositions of 304 stainless steel

(wt%)							
C	Si	Mn	P	S	Ni	Cr	Co
0.05	0.60	0.07	0.026	0.002	0.94	18.59	0.12

ST : 1100°C×40min W.Q.

the cylindrical type with diameter 10 mm at gauge length. The specimens were machined with the loading axis parallel to the working direction of steel plate.

2.2 Test conditions

Test conditions in this study are given in Table 2. In the stress variation creep test, the step up stress creep test, the step down stress creep test and these combination stress creep test were carried out up to rupture. The creep stress changes within 2 or 4 levels. The strain variation fatigue test were carried out by changing strain range of 0.6 % and 1.2 % and by changing number of load cycle contained each strain cycles. The creep test with prior fatigue damage and the fatigue test with prior creep damage were carried out. Strain range of fatigue is two levels, 0.5 % and 1 %, and stress of creep is 215.6 MPa constant. In tension hold creep-fatigue tests with different mean strain, total strain range is two levels, 0.5 % and 0.7 %, and each hold time is 0.1 hour and 1 hour. In the low cycle fatigue test with strain hold time at the zero strain position, strain range is 0.5 % and hold time is 1 hour. All test temperature is 550 °C only, and strain rate of all fatigue test is 0.1 %/sec.

Table 2 Summary of test items

TEST ITEM	WAVE SHAPE
STRESS VARIATION CREEP	
STRAIN VARIATION FATIGUE	
CREEP AFTER FATIGUE	
FATIGUE AFTER CREEP	
MEAN STRAIN CREEP-FATIGUE	
THERMAL STRESS SOFTENING CREEP-FATIGUE	

3 RESULTS AND DISCUSSION

3.1 Creep life on the stress step up and down creep test

The creep damage is evaluated by the summation of damage fractions based on rupture time, $\sum t/t_R$. This evaluation method is supported by many study up to the present (e.g. Robinson et al. 1952). However, in this study, the effect of sufficient load sequence on the stress step up and down creep test was shown. Time to rupture of the materials which are loaded same stress and same loading duration was tending to extend in case of including the step down stress creep. This result give a difference of life prediction by $\sum t/t_R = 1$. Then the life prediction model was proposed. The calculation procedure for time to rupture in case of the step up stress creep is shown in Fig. 1. This concept is essentially based on the constant load creep data with the classical strain hardening theory. Creep time can be calculated from initial point to the end of the steady creep region based on the strain hardening theory. When the creep

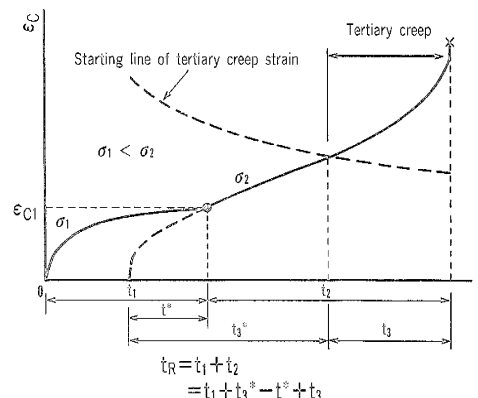


Fig.1 Calculation procedure for time to rupture of step up stress creep

curve get across the starting line of tertiary creep strain which is determined by tertiary creep strain on the constant load creep, tertiary creep starts. The time to rupture of these tests were predicted by the summation of these calculated results and the tertiary creep periods of creep test data under the constant load of the same stress level of the last step.

Creep curve of the stress step up and down creep test is shown in Fig. 2. The predicted creep curve is also shown in this figure. The time parameter $\alpha_C=1$ of the creep strain equation indicates mean value for the amount of scatter of the measurements of creep strain (Yoshitake et al. 1986). Tertiary creep time of the constant load creep test is already found by $t_3 = \alpha_R \cdot t_R$; $\alpha_R=0.506$. When the predicted creep curve by this procedure get across the predicted starting line of tertiary creep strain, the predicted initial point of tertiary creep strain was good agreed with observed tertiary creep.

Predictability of creep rupture time based on this tertiary creep strain limit is shown in Fig. 3. As result of creep life prediction, the summation of damage fractions based on rupture time could evaluate the creep life of the stress step up and down creep tests sufficiently. Furthermore, predictability of creep life can improve by the concept of the tertiary creep strain limit.

3.2 Fatigue life on the strain variation fatigue test

The fatigue damage is evaluated by the summation of damage fractions based on number of load cycles, $\sum N/N_f$. Then, the fatigue damage is given different results by the measuring method of strain range. Predictability of the strain variation fatigue life is shown in Fig. 4. The measuring method of strain range was used the BDS method which was the measuring method in the Japanese elevated temperature structural design guide for class 1 components of FBR. The cycle is counted at the zero strain position in the BDS method. As

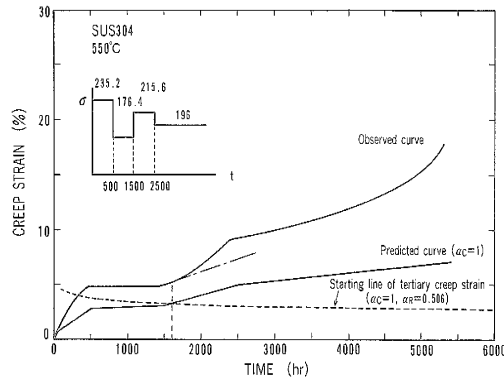


Fig. 2 Initial point of tertiary creep strain

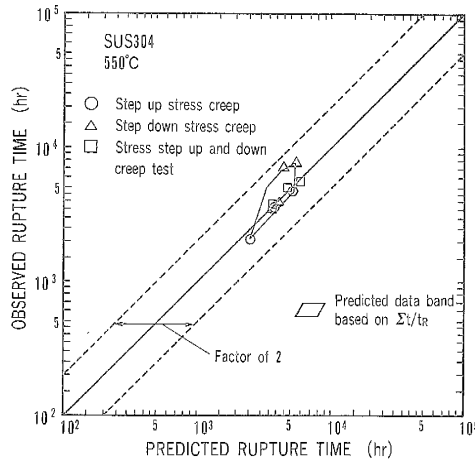


Fig. 3 Predictability of creep rupture time based on tertiary creep strain limit

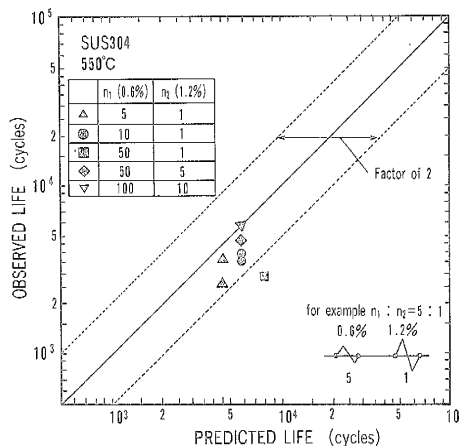


Fig. 4 Predictability of strain variation fatigue life based on BDS

the results, the predicted lives were within a factor of 2 of the observed life. However, the predicted lives were located on un-conservative side. The method based on the tension going strain range showed good agreement with the observed life (see in Fig. 5). This measuring method of strain range was modified original method based on the tension going strain range. The cycle is counted as two times of strain amplitude at the tension going side. Therefore, the modified method based on the tension going strain range is actual, but the method based on the BDS is simple and practical.

3.3 Creep-fatigue life for the prior damaged material

The creep life with prior fatigue damage and the fatigue life with prior creep damage is shown in Fig. 6. The ratio of life reduction for mean life of time to rupture of creep test with prior fatigue damage was less than that of number of cycles to failure of fatigue test with prior creep damage. The creep fatigue damage fraction is shown in Fig. 7. The damage on the creep test with prior fatigue damage was evaluated conservatively, while the damage on the fatigue test with prior creep damage showed good agreement with Campbell diagram. As the results, the load sequence effect was shown. The elongation value of the creep test with prior fatigue damage was not lower than that of as-received material, but the reduction of area was increased. The series of intensive slip of surface of test specimen under load cycles caused local reduction of area as compared with reduction of area on conventional creep tests.

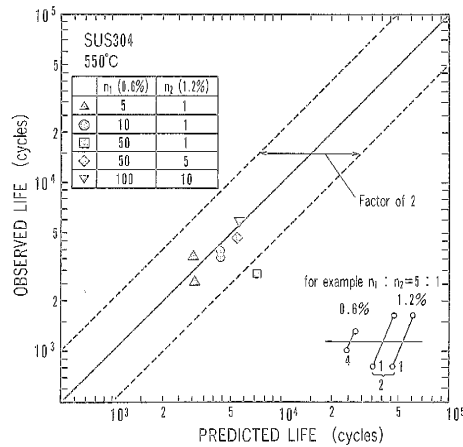


Fig. 5 Predictability of strain variation fatigue life based on modified tension going strain range

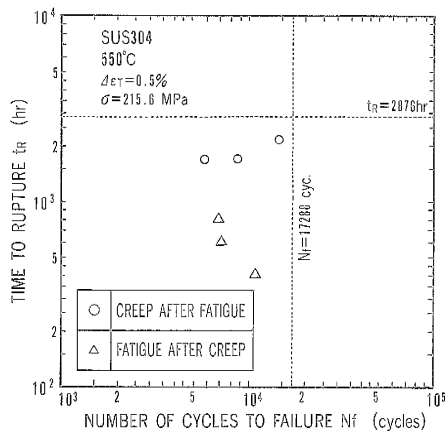


Fig. 6 Comparison of failure life on the combined creep fatigue test

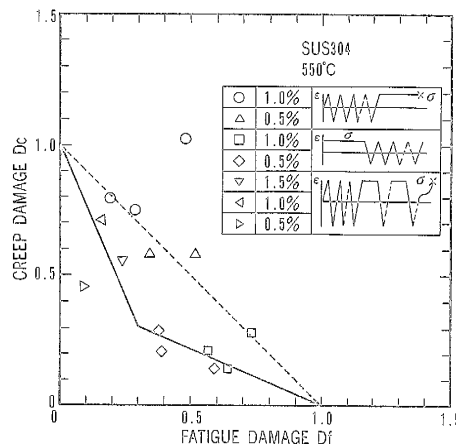


Fig. 7 Creep fatigue damage fraction based on experimental data

3.4 Effect of the mean strain on the creep-fatigue life

Tension hold creep-fatigue lives with different mean strain are shown in Fig. 8. The creep-fatigue life with tension mean strain was compared with the life of zero mean strain with same total strain range. These creep-fatigue lives of both 0.1 hour hold and 1 hour hold was equal whether the mean strain was given or not. Mean stress and creep damage at each cycle on the creep-fatigue tests with tension mean strain and zero mean strain became almost equal after a few cycles. Therefore, the effect of the mean strain on the creep-fatigue life was shown to be negligible.

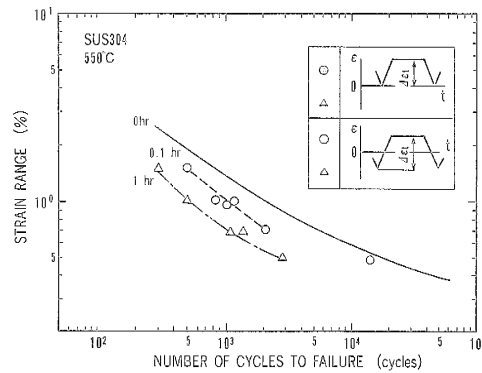


Fig. 8 Effect of the mean strain on the creep-fatigue life

3.5 Effect of the thermal stress softening on the fatigue life

The low cycle fatigue life with strain hold time at the zero strain position in the continuous strain cycles is shown in Fig. 9. The maximum stress range at $1/2N_f$ in this test went down with thermal stress softening by zero strain hold in comparison with that of the continuous fatigue cycles. However, the low cycle fatigue life with zero strain hold was almost the same as that of conventional low cycle fatigue test with the same strain range, 0.5%, in spite of almost same as the maximum stress range between the conventional creep-fatigue test and the low cycle fatigue test with zero strain hold. It was shown from this experiment that the main factor of creep-fatigue life reduction compared with fatigue life was not thermal stress softening by hold but the creep damage during hold periods.

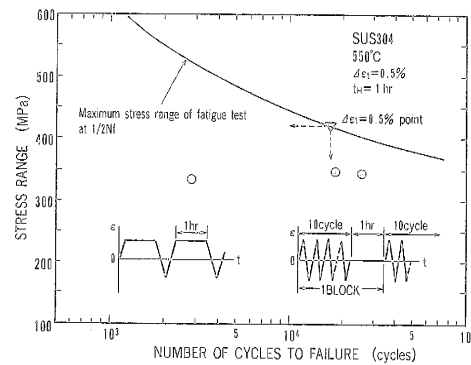


Fig. 9 Effect of the thermal stress softening on the creep-fatigue life

3.6 Creep-fatigue life prediction

Predictability of creep-fatigue life on several loading conditions is shown in Fig. 10. The lives for 109 data points which were included several product forms, 5 heats, were plotted. The creep-fatigue evaluation (PNC method) is based on linear damage fraction rule, that fatigue damage is evaluated from the mean fatigue life corresponding to

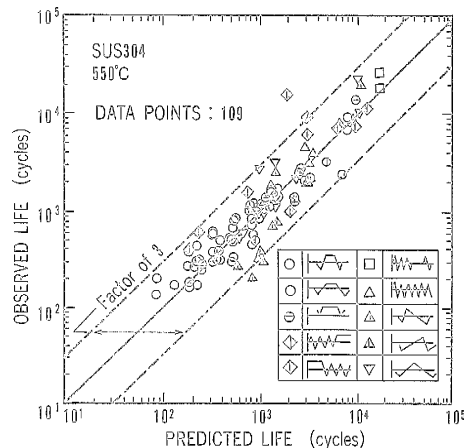


Fig. 10 Predictability of creep fatigue life based on linear damage fraction rule

tension going strain rate and creep damage is evaluated by considering the stress relaxation behavior during strain hold period(Aoto et al. 1987). Predicted lives were within a factor of 3 of the observed lives. It was confirmed that the present creep-fatigue evaluation basis of linear damage fraction rule was applied for the evaluation of life under creep and fatigue interaction on several loading conditions.

4 CONCLUSIONS

Several creep, fatigue and creep-fatigue test for 304 stainless steel were performed to investigate strain history effects to the material strength and to confirm the generality of application of linear damage fraction rule. The summation of damage fractions based on rupture time could evaluate the creep life of the stress step up and down creep tests by the study on pure creep damage. The end of the steady creep region and the time to rupture of those creep tests could be reasonably estimated by application of new concept based on the tertiary creep limit. The fatigue damage was strongly depended on the measuring method of strain range in the strain variation fatigue test. In Creep tests with prior fatigue damage and fatigue tests with prior creep damage, creep and fatigue damage were evaluated by linear damage fraction rule. The effect of the mean strain on the creep-fatigue life was shown to be negligible. It was shown that the main factor of creep-fatigue life reduction compared with fatigue life was not thermal stress softening by hold but the creep damage during hold periods. The creep-fatigue lives included several strain history could be predicted by the present creep-fatigue evaluation method.

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