Study on Creep-Fatigue Life of Irradiated Austenitic Stainless Steel*

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The low cycle creep-fatigue test with tensile strain hold of the austenitic stainless steel irradiated to 2 dpa was carried out at 823 K in vacuum. The applicability of creep-fatigue life prediction methods to the irradiated specimen was examined. The fatigue life on the irradiated specimen without tensile strain hold time was reduced by a factor of 2~5 in comparison with the unirradiated specimen. The fraction of intergranular fracture increased with increasing strain hold time. The decline in fatigue life of the irradiated specimen with tensile strain hold was almost equal to that of the unirradiated specimen. For the irradiated specimen, the time fraction damage rule trends to yield unsafe estimated lives and the ductility exhaustion damage rule trends to yield generous results. However, all of data were predicted within a factor of three on life by the linear damage rule.

Key Words: Creep-fatigue, Irradiation, Austenitic Stainless Steel, Fast Reactor, Time Fraction, Ductility Exhaustion, Linear Damage Rule, Life Prediction

1. Introduction

Austenitic stainless steels are being widely used as a major structural material for liquid metal cooled fast reactors (LMFRs) in view of its good high temperature mechanical properties, compatibility with the sodium coolant and adequate weldability. The excellent heat transfer properties of the sodium coolant transmit any changes in the coolant temperature rapidly to the structure components of LMFRs. The thermal transients that are sufficiently rapid may cause local yielding of the material. Repetition of such transients can therefore result in progressive damage by both creep and fatigue mechanisms. Interaction on these damage processes might result in more

severe damage than the individual mechanisms acting in isolation.

Creep-fatigue evaluation is a key technology in structure design of LMFRs components and a linear damage rule with the life fractions of fatigue and creep lives is widely used in high temperature plant design⁽¹⁾. The creep-fatigue life prediction methods have been studied by the application of a time fraction damage rule or a ductility exhaustion damage rule to the unirradiated material. However, the creep-fatigue data of the irradiated materials is not reported in most.

In this report, a low cycle fatigue testing was carried out to examine the effect of hold time at tension side on fatigue life of the irradiated austenitic stainless steel. The application of the time fraction damage rule and the ductility exhaustion damage rule was tried to the calculation of creep damage for the irradiated material. The experimental creep-fatigue lives were compared with the predictions using a linear damage rule.

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Table 1 The chemical compositions of the material tested

C	Si	Mn	P	S	Cu	Ni	Cr	Nb	V	N	Co	B	Fe
0.0047	0.54	0.78	0.024	0.003	0.09	9.08	18.52	0.02	0.08	0.034	0.05	0.0002	Bal.

Table 2 The mechanical properties of the material tested

Test temperature (K)	0.2% proof stress (MPa)	Ultimate tensile stress (MPa)	Total elongation (%)
300	246	591	69
823	135	393	43

Fig. 1 Dimensions of the specimen designed for push-pull low cycle fatigue testing

2. Experimental Procedure

The material tested was commercially manufactured type 304 stainless steel plate with 1 000 mm in width, 1 600 mm in length and 40 mm in thickness. The material was prepared by hot rolling followed by solution annealing at 1 323 K for 720 second and then water-cooling. This treatment resulted in an average grain size of ASTM No. 5. The chemical composition and mechanical properties of the material are shown in Tables 1 and 2. The material was machined into bottom-ended test specimens with gauge section of 4 mm in diameter and 6 mm in length with the length-axis perpendicular to the rolling direction. The surface of the gauge section was ground with 600 grade silicon carbide paper and 3 μm Al_2O_3 powder and then electropolished to produce a high degree of finish. Moreover, to meet the requirement for laser extensometry, a specimen with double blades at both ends of the gauge section was developed and improved by elasto-plastic finite element calculations. Dimensions of the specimen designed for push-pull low cycle fatigue testing are shown in Fig. 1.

Table 3 Irradiation condition of the material tested

Fluence(n/m^2)		Dose (dpa)	Helium (appm)
Fast neutron ($E>1\text{MeV}$)	Thermal neutron ($E<0.7\text{eV}$)		
$0.5\sim 1\times 10^{25}$	$0.006\sim 2.3\times 10^{25}$	$0.9\sim 1.8$	$0.8\sim 2.5$

Specimens were irradiated in the fuel or beryllium reflector regions of the Japan Materials Test Reactor (JMTR) at 823 K. The irradiation was performed with a peak thermal neutron flux of approximately $7\times 10^{17} \text{ n}/\text{m}^2/\text{s}$ and a fast neutron flux of $2\times 10^{18} \text{ n}/\text{m}^2/\text{s}$ ($E>1 \text{ MeV}$). The fluence level of $1\times 10^{25} \text{ n}/\text{m}^2$ gave a damage level of 1.8 dpa with helium concentration of 2.5 appm at a temperature of 823 K. The irradiation conditions are summarized in Table 3.

Uniaxial strain-controlled cyclic tests were performed on a computer-controlled servohydraulic machine installed in a radiation hot cell of the JMTR. The machine was equipped with a vacuum system offering 10^{-1} Pa environment during elevated temperature testing. Details of testing machine are described elsewhere⁽²⁾. All tests were performed at 823 K which is the irradiation temperature. Specimens were subjected to a reversal triangular strain versus time program beginning with tension at a strain rate of 10^{-3} s^{-1} . Some specimens were subjected to hold time of 360 and 3 600 seconds in maximum tensile strain. Total axial strain ranges were from 0.8% to 1.6%. The fatigue life of the specimen was defined as the number of cycles at which a tension stress reduced to 75% of the maximum stress during cyclic stress testing.

3. Results and Discussion

3.1 Creep-fatigue test

First of all, to examine the effect in aging on fatigue life under irradiation, fatigue characteristics of the aged material were examined. Considering the fluctuation of the temperature under irradiation, the aging temperatures were selected 793, 823, 853 K, and the aging times were 2 400 and 4 800 hour which are corresponded to the irradiation period of the specimens. The fatigue lives of aged specimens were almost equal to those of the solution annealed ones. There was no effect of aging even in tensile and creep tests. The change in microstructure were also examined the solution annealed and the aged materials. There was no difference in their grain size and precipitation of both specimens. It is considered that there is no effect of aging on the mechanical properties and microstructure of the material.

Fatigue lives of the unirradiated and irradiated

Fig. 2 Fatigue lives of the unirradiated and irradiated specimens as the total strain range versus the number of cycles to failure on log-log scale

specimens are plotted in Fig. 2 as the total strain range versus the number of cycles to failure on a log-log scale. The data of the specimens were fitted to a power law equation, using guidance from the Manson-Coffin equation^{(3),(4)}. The following equation results from a least-squares fit to the data of Fig. 2.

$$\Delta\epsilon_t = 3.2N_{f0}^{-0.24} + 53.3N_{f0}^{-0.50} \quad (\text{Unirradiated}) \quad (1)$$

$$\Delta\epsilon_t = 1.2N_{f0}^{-0.17} + 8.0N_{f0}^{-0.31} \quad (\text{Irradiated}) \quad (2)$$

where $\Delta\epsilon_t$ is total strain range. N_{f0} is number of cycles to failure of specimen without strain hold time. The difference in behavior between unirradiated and irradiated specimens is quite clear and appears to be a reduction by a factor of 2 to 5 in fatigue life. The reduction in fatigue life was prominent in low cycles. Irradiation reduces tensile ductility which is a very important factor in low cycle fatigue⁽⁵⁾. Moreover, strength is the controlling factor in high cycle fatigue. Tensile tests for the irradiated specimens were carried out at the same strain rate and temperature of the fatigue test⁽⁶⁾. The results indicated that the ultimate tensile stress of the irradiated specimen was almost the same as that of the unirradiated one, whereas the reduction of area decreased from 83% to 63%. It is considered that the loss of ductility can explain the degradation for fatigue life of the irradiated specimens in Fig. 2.

Figure 3 is replotted to data of unirradiated and irradiated specimens at the total strain range of 1.0% as a relationship between hold time and fatigue life reduction factor (ratio of fatigue life of specimens with strain hold time to that without strain hold time). Data of the literature⁽⁷⁾ are included in Fig. 3. The fatigue lives of the irradiated specimens without strain hold time was calculated using Eq. (2). The fatigue lives of the unirradiated specimens with strain hold time at present work were obtained from standard type specimens without blades ($\phi 8 \times 20$ mm)

Fig. 3 Relationship between fatigue life reduction factor and strain hold time

using another testing machine. The fatigue life decreased with the increase in strain hold time. Though fatigue life on the irradiated specimen without strain hold time was reduced by a factor of 2 - 5 in comparison with the unirradiated specimen, the declining tendency in the fatigue life of the irradiated specimens is similar to the unirradiated ones. So, the creep-fatigue life prediction methods using the unirradiated material was applied to estimate creep-fatigue life of the irradiated material. Fracture surfaces of the irradiated specimen without strain hold time and with a strain hold time of 360 s and 3 600 s are shown in Fig. 4. The observation from viewing the entire surface of the irradiated specimen without strain hold time showed that the fracture was primarily transgranular with a large amount of striation as shown in Fig. 4 (a). The fraction of intergranular fracture increased with increasing strain hold time. Takahashi et al.⁽⁸⁾ reported the similar trend of the unirradiated type 316 stainless steel. It is believed that the reduction of fatigue life is attributed to the increase in the fraction of intergranular fracture.

3.2 Creep-fatigue life evaluation

Creep-fatigue life assessment of irradiated specimens with tensile strain hold was carried out using the linear damage rule. The fatigue damage (D_f) was calculated by Minor's rule (the ratio of cycles to failure).

$$D_f = \frac{N_f}{N_{f0}} \quad (3)$$

where N_f denotes the number of cycles to failure of specimen with strain hold time. N_{f0} and N_f were obtained from low cycle fatigue test at a total strain range of 1%.

The creep damage (D_c) was calculated by two approaches. One is a time fraction damage rule (Eq. (4)) which has been used in design or integrity

Fig. 4 Fracture surfaces of irradiated specimens at 1.0% total strain range with different strain hold time of (a) 0 s, (b) 360 s and (c) 3 600 s

assessment of high temperature reactor plants and is based on ASME Code Case N-47⁽¹⁾, the other is a ductility exhaustion damage rule (Eq.(5)). The equations for the calculation of each damage were described as follows:

$$D_{c,t} = N_f \int_0^{t_h} \frac{dt}{t_r} \quad (4)$$

$$D_{c,d} = N_f \int_0^{t_h} \frac{d\epsilon_c}{\epsilon_f} \quad (5)$$

where t_h , t_r , ϵ_c , ϵ_f are strain hold time of 1 cycle, time to rupture, creep strain and fracture ductility, respectively. $D_{c,t}$ was calculated from stress relaxation curve at a half cycle of N_f and creep rupture time-stress curves. The stress relaxation curve of the irradiated specimen with hold time of 3 600 s is shown in Fig. 5 as an example. For the creep damage evaluation, the basic mechanical properties of unirradiated

Fig. 5 Stress relaxation behavior of the irradiated specimen with 3 600 s holding time at a half cycle of N_f

Fig. 6 Creep rupture curves of the unirradiated and the irradiated specimens for evaluation of creep damage

and irradiated specimens obtained by monotonic creep rupture tests⁽⁹⁾ were used. Figure 6 shows the creep rupture time-stress curves of the unirradiated and irradiated specimens at 823 K. The creep strain ϵ_c was obtained from the following equation;

$$d\epsilon_c = \frac{d\sigma}{E} \quad (6)$$

where E is Young's modulus. The fracture ductility, ϵ_f , is represented by the following equation;

$$\epsilon_f = \ln\left(\frac{100}{100 - RA}\right) \quad (7)$$

where RA is reduction of area. The relationship between stress and fracture ductility of the irradiated specimens used for evaluation of creep damage is shown in Fig. 7.

In order to investigate the applicability of the time fraction damage rule or the ductility exhaustion damage rule to the irradiated specimen, the creep damage was simultaneously calculated by the ductility exhaustion damage rule to compare with the time fraction damage rule. Figure 8 shows evaluation results of creep and fatigue damage. The following data have been repeated on Fig. 8: the damage of the

Fig. 7 Relationship between stress and fracture ductility used for evaluation of creep damage

Fig. 8 Evaluation results of creep and fatigue damage

unirradiated specimens calculated using the time fraction damage rule and the ductility exhaustion damage rule. The creep damage of the time fraction damage rule is smaller than that of the ductility exhaustion damage rule for the unirradiated and irradiated specimens. Moreover, the creep damage of irradiated specimens became remarkable with the increase in strain hold time. This result is correspondent with the increase in the intergranular fracture of fracture surface shown in Fig. 4.

The comparison between predicted and experimental creep-fatigue lives is shown in Fig. 9. The linear damage rule was applied to the prediction in Fig. 9. All of data were predicted within a factor of three on life by the linear damage rule. For the unirradiated and irradiated specimens, the predictions by the time fraction damage rule are unsafe as compared with the experimental creep-fatigue lives. Such tendency was reported by Nonaka et al.⁽¹⁰⁾ for the unirradiated type 316FR which is modified type 316 stainless steel. The tendency of the predicted creep-fatigue life of the irradiated specimens using

Fig. 9 Predictions of creep-fatigue life based on two damage evaluation methods

the time fraction damage rule or the ductility exhaustion damage rule is similar to that of the unirradiated ones, namely the former tends to yield unsafe estimated lives and the latter tends to yield generous results.

4. Conclusions

The low cycle creep-fatigue test with tensile strain hold of the austenitic stainless steel irradiated to 2 dpa was carried out at 823 K in vacuum. The applicability of creep-fatigue life prediction method to the irradiated specimens was examined. The following conclusions were obtained.

- (1) The declining tendency in the fatigue life of the irradiated specimens with strain hold time is similar to the unirradiated ones.
- (2) The fraction of intergranular fracture increased with increasing strain hold time.
- (3) The application of the time fraction damage rule evaluated the creep-fatigue life in the non-safe side.
- (4) For the irradiated specimen, the time fraction damage rule tends to yield unsafe estimated lives and the ductility exhaustion damage rule tends to yield generous results.

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