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Evaluation of in-pile and out-of-pile stress relaxation in 316L stainless steel under uniaxial loading

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Abstract

Stress relaxation of tensile type specimens under fast neutron irradiation at 288 °C has been studied for 316L stainless steel (SS) in the Japan Materials Testing Reactor. In-pile stress-relaxation tests were carried out at fast neutron fluence levels of 1.3×10^{24}, 5.5×10^{24} and 1.5×10^{25} n/m^2 ($E > 1$ MeV). These tests were carried out at the applied total strain levels of 0.06%, 0.1%, 0.3% and 0.75%. In order to evaluate the thermal stress-relaxation behavior and to distinguish it from the irradiation induced stress-relaxation behavior, out-of-pile stress-relaxation tests were also performed at 288 °C in air using an electric furnace. This paper describes results of in-pile and out-of-pile stress-relaxation tests on 316L SS tensile specimens. These results are compared with the literature data by Foster et al. [J. Nucl. Mater. 252 (1998) 89] which were mainly obtained from bend beam specimens. Moreover, these experimental results are compared with analytical results obtained using Nagakawa's model [J. Nucl. Mater. 212–215 (1994) 541].

1. Introduction

Irradiation assisted stress corrosion cracking (IASCC) caused by the simultaneous effects of neutron irradiation and high temperature water environments is considered to be one of the major concerns of in-core structural materials not only for light water reactors but also for water-cooled fusion reactors. It is of interest to evaluate the stress state under irradiation environment, because the stress is one of the key factors for the IASCC.

Stress-relaxation tests have been performed mainly using bend specimens for several structural materials by Causey et al. [1], Kenfield et al. [2] and Wire and Straalsund [3]. However, there are only a few results available, on stress-relaxation tests using tensile type specimens. Stress relaxation of tensile type specimens under fast neutron irradiation at 288 °C has been studied for 316L stainless steel (SS) in the Japan Materials Testing Reactor (JMTR). In-pile stress-relaxation tests were performed at three different fast neutron fluence levels on 316L SS.

This paper describes the results of in-pile and out-of-pile stress-relaxation tests on 316L SS tensile specimens and these results are compared with the literature data by Foster et al. [4] which were mainly obtained from bend beam specimens. Moreover, these experimental results are compared with the analytical results obtained using Nagakawa's model [5].

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2. Experimental procedure

The chemical composition of the 316L SS used in this study is listed in Table 1. This material was solution annealed at 1065 °C for 77 min. The geometry of specimens used in the present work is shown in Fig. 1. The total specimen length was 100 mm and the length and diameter of the gage section were 30 and 3 mm, respectively. In order to achieve the target strain at room temperature, specimens with a strain gage were strained in a tensile test machine up to the target strain level and then fixed using the constrained outer tube and double nuts as shown in Fig. 1. After the specimen was demounted from the tensile test machine, the level of strain accumulated on the specimen during the test was measured by a remote displacement measuring apparatus.

The experimental conditions of the stress-relaxation tests on 316L SS are listed in Table 2. The applied total strain on the targets were 0.06%, 0.1%, 0.3% and 0.75%, and the levels of the fast neutron fluence were 1.3×10^{24}, 5.5×10^{24} and 1.5×10^{25} n/m^2 ($E > 1$ MeV). The solution-annealed 316 SS has a flow stress of about 200 MPa which corresponds roughly to about 0.1% elastic strain. It is expected that for the specimens pre-strained to 0.06% and 0.1% strain, the deformation is primarily elastic while for the specimens pre-strained to 0.3% and 0.75% strain, the deformation will contain both elastic and plastic components. Thus, the pre-irradiation thermomechanical condition will differ with the 0.3% and 0.75% pre-strained samples containing significantly more dislocations than the samples pre-strained to 0.06% and 0.1% strain. In order to evaluate the thermal stress-relaxation behavior and to identify the pure irradiation induced stress-relaxation behavior, out-of-pile stress-relaxation tests were also performed at 288 °C in air using an electric furnace. The thermal stress-relaxation behavior was measured by strain gages attached to the specimen and the distance between two marked points on the specimen was measured at room temperature.

The principle of the stress-relaxation phenomenon is given by

$$\varepsilon_t = \varepsilon_e + \varepsilon_p = \frac{\sigma}{E} + \varepsilon_p = \text{constant}, \tag{1}$$

where ε_t is the total strain, $\varepsilon_e (= \sigma/E)$ is the elastic strain and ε_p is the plastic strain. The plastic strain ε_p^* necessary to reduce the elastic stress from σ_0 to σ is given by

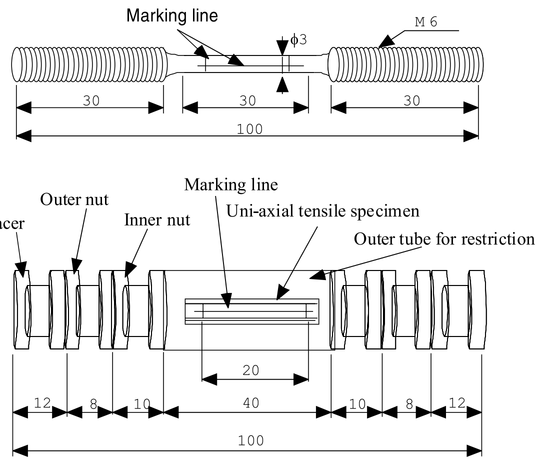

Fig. 1. Geometry of the specimens used in this study.

Table 2
Experimental conditions of irradiation induced stress-relaxation tests

Specimen no.	Holding strain (%)	Temperature (°C)	Fluence (n/m^2 ($E > 1$ MeV))
1	0.06	288	9.30×10^{23}
5	0.06	288	4.70×10^{24}
9	0.06	288	1.60×10^{25}
2	0.1	288	9.30×10^{23}
6	0.1	288	4.70×10^{24}
10	0.1	288	1.60×10^{25}
3	0.3	288	9.30×10^{23}
7	0.3	288	4.70×10^{24}
11	0.3	288	1.60×10^{25}
4	0.75	288	9.30×10^{23}
8	0.75	288	4.70×10^{24}
12	0.75	288	1.60×10^{25}

$$\varepsilon_p^* = \frac{\sigma_0 - \sigma}{E}. \tag{2}$$

Since it is difficult to measure directly the stress state in the specimen during neutron irradiation in the JMTR, it is assumed that the displacement applied to the specimen is constant under irradiation. We evaluated the amount of stress relaxation by measuring the distance between two marked points on the tensile specimens by a remote displacement measuring apparatus before and after irradiation. In this apparatus, the irradiated tensile specimen was positioned using a manipulator, and the

Table 1
Chemical composition of 316L SS (wt%)

C	Si	Mn	P	S	Ni	Cr	Mo	Fe
0.08	0.51	0.95	0.018	0.006	12.58	16.49	2.16	Balance

specimen stage was moved in the vertical direction by a remote electric motor. A CCD camera using a 200× magnification lens was used to observe the surface condition of the specimen. The distance between two marked points was determined by measuring the distance of the specimen stage moved in the vertical direction.

3. Experimental results and discussion

The experimental results on the radiation-induced stress relaxation at 288 °C are shown in Fig. 2. Stress relaxation is referred to the ratio of the instantaneous stress and the initial stress. The fast neutron fluence was determined for each specimen after irradiation. Thermal stress relaxation is not taken into account in this figure. The instantaneous stress and the initial stress are given by

$$\sigma = E\left(\varepsilon_e - \varepsilon_p'\right), \tag{3}$$

$$\sigma_0 = E\varepsilon_e, \tag{4}$$

where σ is the instantaneous stress, σ_0 is the initial stress, E is the Young modulus, ε_e is the elastic strain and ε_p' is the plastic strain by irradiation creep. Therefore, stress relaxation is given as follows,

$$\frac{\sigma}{\sigma_0} = \frac{\varepsilon_e - \varepsilon_p'}{\varepsilon_e}. \tag{5}$$

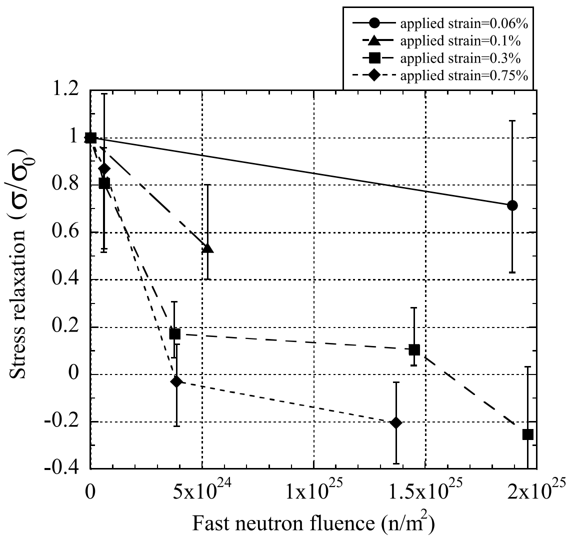

Fig. 2. Dose dependence of radiation-induced stress relaxation measured at 288 °C for 316L SS.

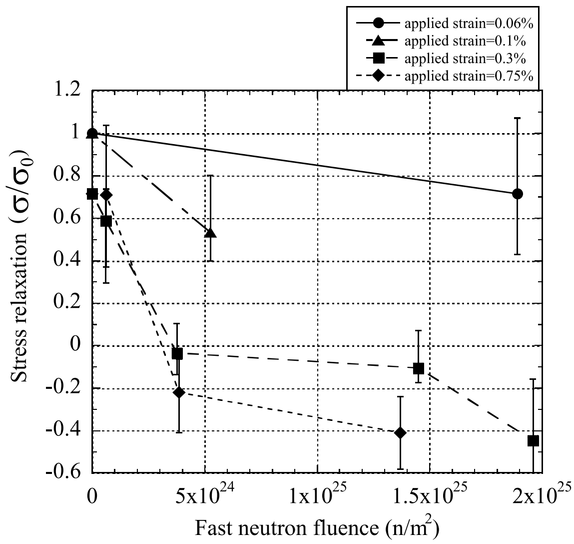

Fig. 3. Stress relaxation corrected for thermal relaxation between room temperature and 288 °C.

In Eq. (5), $\varepsilon_e - \varepsilon_p'$ was derived from the measured data and ε_e was evaluated from the stress–strain curve at room temperature. The stress relaxation increases with increasing neutron fluence. The tendency is observed that stress relaxation under a large initial stress is larger than that under small initial stress. But there is no evidence for a systematic dependence of the residual stress ratio on the initial stress level within the data scatter [1–3]. Therefore, it is necessary to evaluate this tendency with a number of relaxation data using tensile type specimens.

The experimental results with the thermal relaxation data between room temperature and 288 °C are shown in Fig. 3. The instantaneous stress for the thermal relaxation is given by

$$\sigma = E\left(\varepsilon_e - \varepsilon_{th} - \varepsilon_p'\right), \tag{6}$$

where ε_{th} is the strain by thermal relaxation. In Eq. (6), ε_{th} is 0.03% at $\varepsilon_e + \varepsilon_p > 0.08\%$ which was evaluated from stress–strain curves at room temperature and 288 °C. The modified stress relaxation is found by subtracting the thermal relaxation from the total stress relaxation. The effect of thermal relaxation is observed at the initial stage of relaxation behavior, but the tendency of the overall relaxation behavior is the same as the results in Fig. 2. The error in the strain measurement after irradiation was large as shown by the error bars in Figs. 2 and 3.

The experimental results were compared with literature data and the calculated data are shown in Fig. 4. The neutron fluence was converted to displacements per atom (dpa) in this figure. The literature data [2,4] are

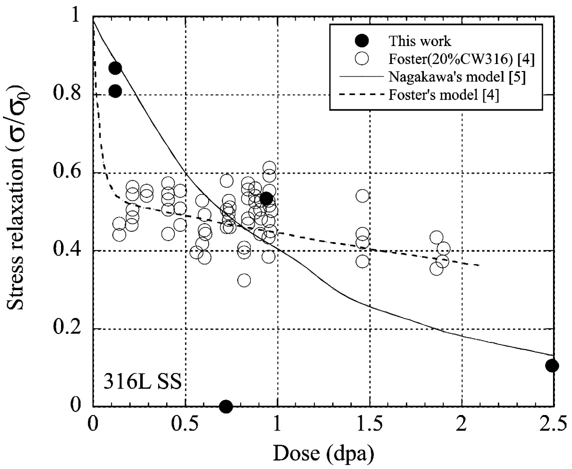

Fig. 4. Comparison between experimental results and literature data including calculated data from Nagakawa [5].

stress-relaxation test results from experiments performed in EBR-II. The samples were fabricated using 20% cold worked 316 SS. Stress relaxation was measured at 370 °C. The dotted line is the calculated stress relaxation using an irradiation creep correlation for bend specimens in the EBR-II [4]. This calculated results can be described as follows [4]:

$$\sigma/\sigma_0 = \exp\{-E[A_1(1-\exp(-A_2 f)) + A_3 f]\}, \tag{7}$$

where E is the elastic modulus, f is the displacement dose and A_1, A_2 and A_3 are the irradiation creep coefficients. Although the literature data show that the stress relaxes rapidly at the onset of the initial irradiation and then stress relaxation decreases slowly from a value of about 0.5 at 0.15 dpa to about 0.4 at 1.9 dpa, the stress relaxation for the tensile specimens decreased smoothly with increasing dpa in this study. It is considered that this tendency is caused by the difference in irradiation conditions between EBR-II and JMTR, and the difference in stress states.

The solid line shows the calculated results according to Nagakawa's model [5] for solution annealed 316 SS at 300 °C. The calculated conditions of initial stress and neutron flux were 300 MPa and 10^{-6} dpa/s, respectively. This model is based on the kinetic analyses of nucleation and growth of defect agglomerates and of point defect absorption by network dislocations and by defect agglomerates under the influence of an external stress. The amount of stress reduction $\Delta\sigma$ by the total plastic strain $\Delta\varepsilon_p$ produced by all of the four mechanisms during each iteration step was evaluated using the equation

$$\frac{d\sigma}{dt} = -E\frac{d\varepsilon_p}{dt} \Rightarrow \Delta\sigma = -E\Delta\varepsilon_p. \tag{8}$$

As for the comparison between the experimental and the calculated results, the calculated results from Nagakawa's model agree well with the experimental results presented here, especially at low doses as shown in Fig. 4. The experimental stress relaxation under a large initial stress is larger than that under small initial stress and is caused by the effect of dislocation density as considered in Nagakawa's model. That is, the dislocation density at a large initial stress is higher than that at a lower initial stress.

4. Summary

In-pile uniaxial stress-relaxation tests on solution annealed type 316L SS using tensile type specimens were performed in the JMTR. This study revealed that stress relaxed with increasing neutron fluence. It was observed that the stress relaxation under a large initial stress was higher than that under a small initial stress.

In future work, it will be necessary to modify the method for measurement of the amount of stress relaxation of the tensile specimen because the measured data from the irradiated specimens include large measurement errors.

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References

[1] A.R. Causey, G.J.C. Carpenter, S.R. Macewen, J. Nucl. Mater. 90 (1980) 216.
[2] T.A. Kenfield, H.J. Busboom, W.K. Appleby, J. Nucl. Mater. 66 (1977) 238.
[3] G.L. Wire, J.L. Straalsund, J. Nucl. Mater. 64 (1977) 254.
[4] J.P. Foster, E.R. Gilbert, K. Bunde, D.L. Porter, J. Nucl. Mater. 252 (1998) 89.
[5] J. Nagakawa, J. Nucl. Mater. 212–215 (1994) 541.