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Effect of helium to dpa ratio on fatigue behavior of austenitic stainless steel irradiated to 2 dpa

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Abstract

The effect of helium due to nuclear transmutation reactions during neutron irradiation on low cycle fatigue life of type 304 stainless steel was investigated. The specimens were irradiated in spectrally tailored capsules in the Japan Materials Testing Reactor (JMTR) at a temperature of 823 K to a neutron fluence of approximately 1×10^{25} n/m^2 ($E > 1$ MeV) and helium levels of 0.8, 2.5 and 8.1 appm. The low cycle fatigue tests were performed in total axial strain ranges of 0.8–1.6% at 823 K. A laser extensometer was used for controlling the axial strain of a specimen under cyclic testing. The difference between unirradiated and irradiated specimens is quite clear and appears to be a reduction by a factor of 2–5 in fatigue life. The helium concentration of the specimen is not the main factor to shorten fatigue life in the present experimental condition.

1. Introduction

Stainless steels have been widely used as structural and core component materials of light water and fast breeder reactors. Even in fusion reactors, stainless steels are still candidate alloys. The difficulty in designing and testing these materials is proceeding in the absence of a relevant neutron environment. Neutron irradiation in a fusion reactor environment has two important features that are missing in fission reactors. One is the high-energy displacement cascade and the other is the amount of helium and hydrogen produced by 14 MeV neutrons in the stainless steels. In particular, helium atoms have effects on swelling and such mechanical properties as ductility and fatigue.

As for austenitic stainless steels, irradiation with neutron spectrum tailoring has given useful data for fusion, because helium generation by the Ni two-step reaction can be adjusted to atomic displacement damage. The main purpose of the present investigation is to evaluate the effect of helium to displacement damage ratio (He/dpa) on fatigue life of type 304 stainless steel. It is believed that, the data obtained are useful for comprehending the effect of He/dpa on the fatigue behavior of austenitic stainless steel for fusion reactors.

2. Experimental procedure

2.1. Specimen preparation

The material tested was commercially manufactured type 304 stainless steel plate with 1000 mm in width, 1600 mm in length and 40 mm in thickness. The material was prepared by hot rolling followed by solution annealing at 1323 K for 720 s and rapid 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 a gauge section 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.

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Table 1
Chemical composition of the material tested (wt%)

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
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

Dimensions of the specimen designed for push–pull low cycle fatigue testing are shown in Fig. 1.

2.2. Neutron irradiation

Specimens were irradiated in the fuel or beryllium reflector region of the Japan Materials Test Reactor (JMTR) at 823 K. Irradiation utilizing a neutron spectrum tailoring method was carried out in the JMTR in order to control the He/dpa level of the specimens. Three types of capsules were specially designed, namely thermal neutron shielding, normal, and a thermal neutron trapping type. In the thermal neutron shielding capsule, a cadmium shield surrounds the specimens in order to reduce the thermal neutron flux and achieve a lower helium to dpa ratio. In the thermal neutron trapping capsule, a graphite shield surrounds the specimens to enhance the thermal neutron flux and achieve a higher helium to dpa ratio. The details of this irradiation are described elsewhere [1]. The normal irradiation in the JMTR was performed with a peak thermal neutron flux of approximately 7×10^{17} n/m^2/s and a fast neutron flux of 2×10^{18} n/m^2/s (E > 1MeV). The fluence level of 1×10^{25} n/m^2 resulted in a damage level of 1.8 dpa with helium concentration of 2.5 appm at a temperature of 823 K. This irradiation resulted in a helium to dpa ratio of 1.4 appm He/dpa. Details of the normal, thermal shielding and thermal trapping irradiation conditions can be found in Table 3.

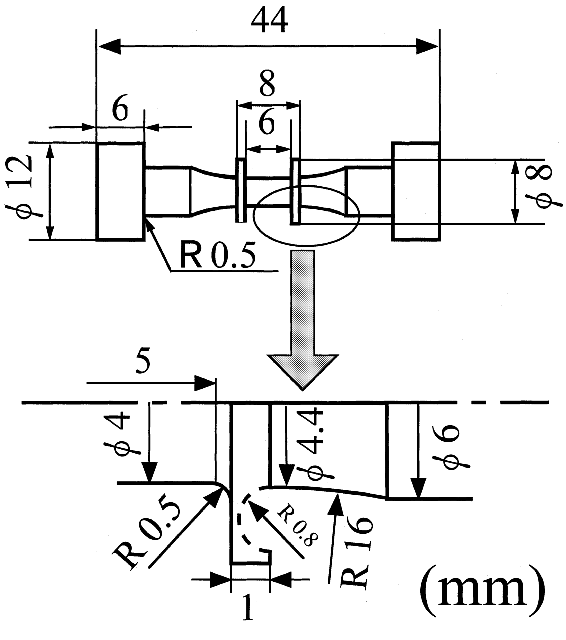

Fig. 1. Dimensions of the specimen designed for low cycle fatigue testing.

2.3. Low cycle fatigue testing

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. The specimen heating was accomplished by an electric heater surrounding the specimen. All tests were performed at an irradiation temperature of 823 K. Specimens were subjected to a reversed 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 s in maximum tensile strain to make the effect of helium to dpa ratio clear. Axial strain ranges used were 0.8–1.6%.

Table 3
Irradiation conditions of normal, thermal shield and thermal trap capsules in the experiment

Irradiation capsule	Fluence (n/m^2)		Dose (dpa)	Helium (appm)
	Fast (E > 1 MeV)	Thermal (E < 0.683 eV)		
Normal	1.0×10^{25}	5.1×10^{24}	1.8	2.5
Thermal shielding	0.5×10^{25}	5.8×10^{22}	0.9	0.8
Thermal trapping	0.7×10^{25}	2.3×10^{25}	1.3	8.1

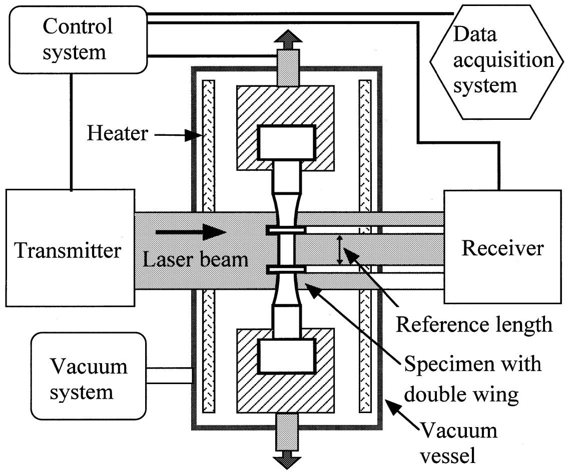

Fig. 2. Schematic drawing of the strain measurement system using a laser extensometer for fatigue testing.

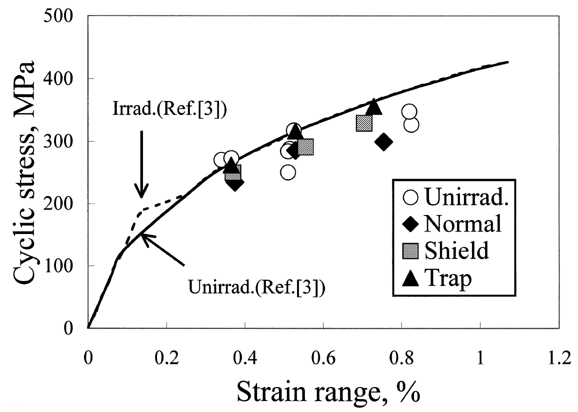

Fig. 3. Relationship between cyclic stress and strain for type 304 stainless steel irradiated in the JMTR at 827 K and tested at the irradiation temperature.

A laser extensometer was used for controlling the axial strain of a specimen under cyclic testing. The technique allows strain measurements without contact on the specimen. A schematic drawing of the strain measurement system is shown in Fig. 2.

The laser device included a semiconductor type laser transmitter and a receiver, which aligned with one another. The accuracy of the laser strain measurement system is 0.1 μm. The beam has a high scanning frequency (480 Hz) which enables us to obtain a patch 55 mm wide, in which the specimen to be measured is placed. In practice, a ratio of the maximum frequency to the sampling frequency should be above 10 in order to obtain a sufficient number of measuring points [2]. The ratio was about 20 in this experiment. Strain measurement requires the definition of a reference length. The distance between the blades was determined as the reference length (6 mm) as shown in Fig. 2.

The stress–strain hysteresis loops have been recorded during each experiment. All specimens, both unirradiated and irradiated, were loaded remotely using the same procedure in order to avoid differences in alignment. The fatigue life of the specimen was defined as the number of cycles at which the tensile stress decreased to 75% of the maximum stress during cyclic stress testing.

3. Results and discussion

Relationships between cyclic stress and strain range of unirradiated and irradiated specimens are plotted in Fig. 3 using the cyclic stress values at one half the number of cycles to failure. There appears to be little difference between unirradiated and normal irradiated materials. A similar result was observed by de Vries in DIN 1.4948 (similar to type 304 stainless steel) irradiated and tested at 823 K [3]. The normal irradiated specimen probably exhibited a similar behavior due to irradiation-assisted recovery and coarsening of the microstructure with irradiation at high temperature [4]. No difference among normal, shielding and trapping irradiation specimens and hence influence of helium concentration on the cyclic stress–strain relationship are observed.

Fig. 4 shows the variation in axial stress amplitude as a function of cycles for unirradiated and irradiated specimens tested in continuous cycling at a total strain range of 1% at 823 K. The vertical axis, stress amplitude, denotes one half the difference between the maximum tensile and the minimum compressive stress within one

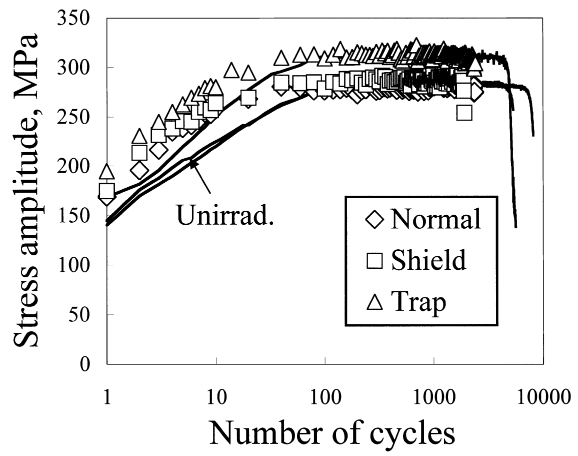

Fig. 4. Variation in axial stress amplitude as a function of cycles for unirradiated and irradiated specimens tested in continuous cycling at 823 K.

cycle. The stress amplitudes of the irradiated specimens were higher than the unirradiated ones at the first cycle. This behavior is expected from tensile tests under similar conditions [1]. In the low-cycle regime, the stress amplitude of both unirradiated and irradiated specimens increased with increasing the number of cycle and then reached almost the same level of saturation stress. This behavior was previously observed in this material under the same test conditions [3]. The stress amplitudes of both unirradiated and irradiated specimens saturated after about 400 cycles and 40 cycles, respectively. It seems that the irradiation induced defects cause the saturation of stress amplitude at a lower number of cycles during fatigue tests.

Fatigue life of unirradiated and irradiated specimens are plotted in Fig. 5 as the total strain range versus the number of cycles to failure on a log–log scale. The data of the unirradiated specimens were fitted to a power law equation, using guidance from the universal slopes

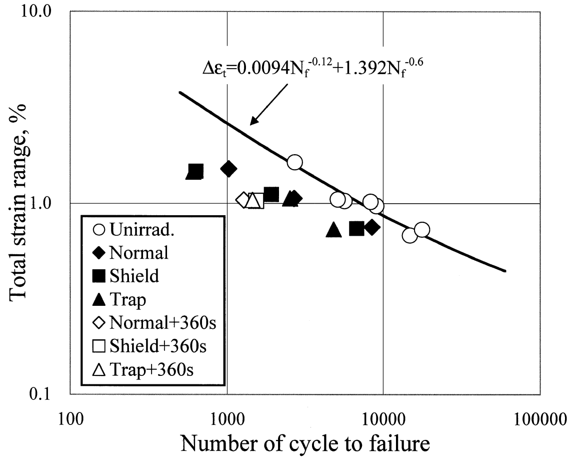

Fig. 5. Fatigue life of unirradiated and irradiated specimens as the total strain range versus the number of cycles to failure on a log–log scale.

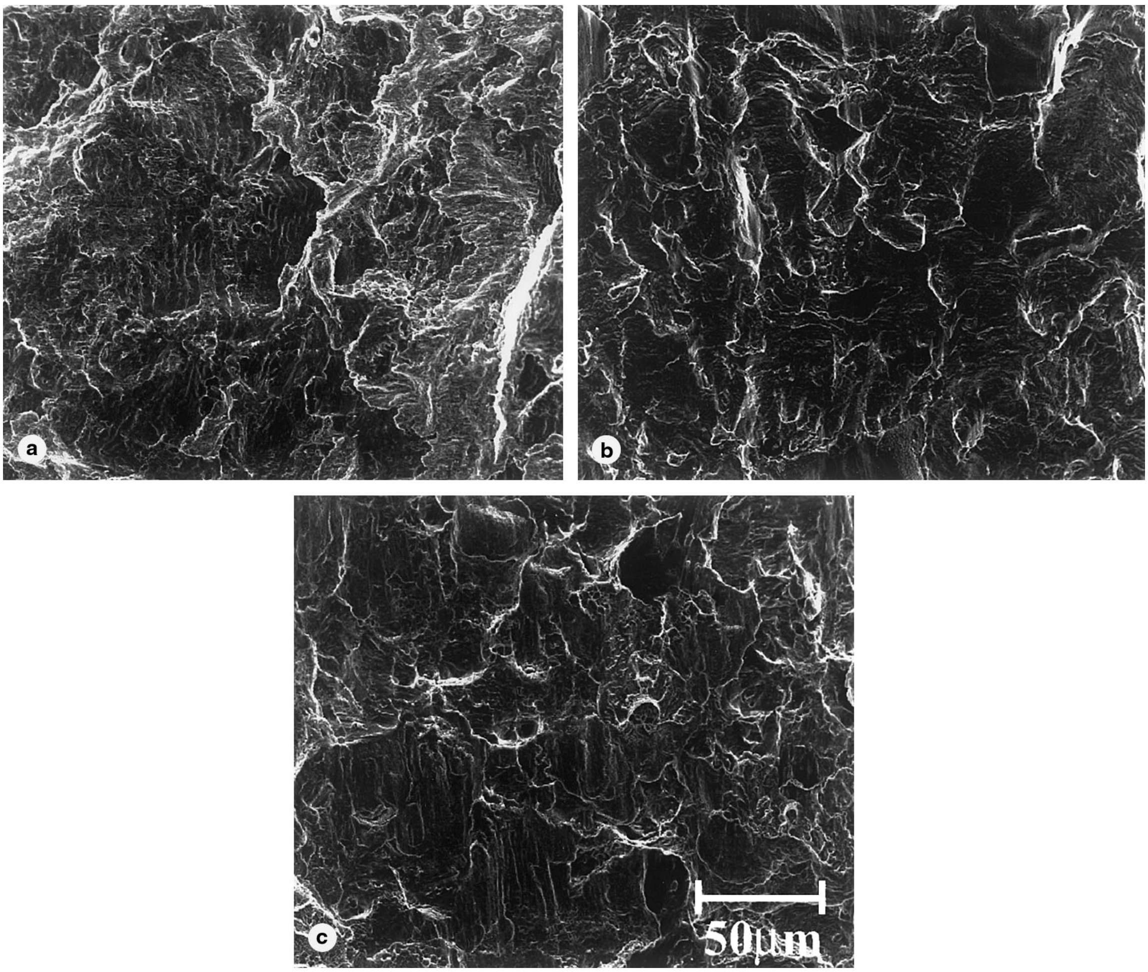

Fig. 6. Fracture surfaces of irradiated specimens at 1.5% strain range with different He/dpa levels of (a) 2.5, (b) 0.8 and (c) 8.1.

equation [5]. The following equation, plotted in Fig. 5, results from a least-squares fit to the data:

$$\Delta\varepsilon_t = 0.0094 N_f^{-0.12} + 1.392 N_f^{-0.6}, \quad (1)$$

where $\Delta\varepsilon_t$ is the total strain range and N_f is the number of cycles to failure.

The difference between unirradiated and irradiated specimens is quite clear and appears to be a reduction by a factor of 2–5 in fatigue life. The reduction in fatigue life was prominent in low cycle fatigue. In preliminary tests, the thermally aged specimens which were aged to the same thermal condition as the irradiated specimens showed no discernible differences in fatigue life from the unaged specimens. For the universal slopes equation, the coefficients of the first- and second-terms on the right-hand side of Eq. (1) are dependent on the ultimate tensile strength and the logarithmic ductility generally evaluated from the reduction of area, respectively. Irradiation reduces tensile ductility and ductility is a very important factor in low cycle fatigue [6]. Moreover, strength is the controlling factor in high cycle fatigue. These effects are incorporated into prediction methods such as the universal slopes [5] and the characteristic slopes methods [7]. Tensile tests for the normal irradiated specimens were carried out at the same strain rate and temperature as the fatigue tests [1]. The results indicated that the ultimate tensile strength of the normal irradiated specimens was almost the same as that of the unirradiated ones, whereas the reduction of area decreased from 83% to 63%. It is considered that the loss of ductility can explain the degradation of fatigue life in Fig. 5. On the other hand, de Vries [3] and Elen et al. [8] reported no significant effect on the fatigue life after irradiation at 823 K. It seems that the difference between their results and the present results might be attributed to lower fluence in their tests.

Fig. 5 also shows no effect of helium concentration on fatigue life. Significant degradation of fatigue life was not observed in irradiated specimens with different levels of helium concentration, though the fatigue life of the specimens with hold time was lower than the specimens without hold time. A similar trend was shown by Sonnenberg et al. [9] using He-implanted type 316 stainless steel. It has been speculated that the cyclic motion of dislocations associated with fatigue could sweep helium atom clusters to sinks such as grain boundaries where they will accumulate until sufficient concentration can cause failure [10]. It is believed that the mechanism could depend on the temperature. Tavassoli et al. [11] reported helium influencing fatigue life of type 304 stainless steel above 973 K. Following testing, the fracture surfaces were examined in a scanning electron microscope to study the fracture morphology. The fracture surfaces for the unirradiated and the irradiated (normal, thermal shielding and thermal trapping) specimens at a total strain range of 1.6% are shown in Fig. 6. The observation from viewing the entire surface of each specimen was that the fractures were primarily transgranular with a large amount of ductile rupture. There was hardly a difference in the fracture mode. It is concluded that helium concentration in the specimen is not the main factor in fatigue life reduction in the present experimental conditions.

4. Conclusion

The results of this work are summarized as follows:

1. An influence of helium concentration on cyclic stress–strain relationship was not observed.
2. The stress amplitude of the irradiated specimens saturated at a lower number of cycles, though the stress amplitude of both unirradiated and irradiated specimens was almost the same.
3. Irradiation caused a reduction by a factor of 2–5 in fatigue life of the specimens.
4. The helium concentration of the specimen is not the main factor in fatigue life reduction in the present experiment.

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