Fatigue Behavior of Type 316 Stainless Steel Following Neutron Irradiation Inducing Helium*

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Since a tokamak reactor operates in a cyclic mode, thermal stresses will result in fatigue in structural components, especially in the first wall and blanket. There has been limited work on fatigue in irradiated alloys[1] but none on irradiated materials containing significant amounts of irradiation-induced helium. To provide scoping data and to study the effects of irradiation on fatigue behavior, 20%-cold-worked type 316 stainless steel from the MFE reference heat† was studied.

Experimental Procedure

Hourglass specimens with minimum gage diameters of 3.18 mm (0.125 in.) were irradiated in the High Flux Isotope Reactor (HFIR) in peripheral target positions, providing both a high rate of displacement damage and rapid helium production from interaction of thermal neutrons with nickel. A helium gas gap controlled the temperature.[2] The experiment was monitored by inclusion of low-melting alloys.

Tests were performed on a servo-hydraulic testing system equipped for remote operation.[3] Specimens were tested in a vacuum at pressures from 10^{-5} to 10^{-4} Pa. The gage section of the specimen was maintained at 430 ± 5°C, remaining constant within ±1°C during the test. Strain was measured at the minimum cross section with a diametral extensometer. The diametral signal in turn was converted to an equivalent axial strain through a strain computer for machine control. A fully reversed ramp function providing a strain rate of 4×10^{-3}/s was used. Specimens were cycled to complete separation. Crack initiation was estimated from continuous stress plots by determining the point of load drop from cracking.

Results and Discussion

Results of the tests appear in Table 1 and in Fig. 1. The irradiated specimens show a reduction in fatigue life of about a factor of 3-10.

The scatter in the data from the irradiated specimens is significantly larger than the control data. However, the specimens were irradiated over a fluence range of greater than a factor of 2. The fluence dependence of fatigue life appears to be complex and is not understood at the present time. In addition to fluence variation, other irradiation parameters such as temperature typically result in large scatter of mechanical properties data.

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†Magnetic Fusion Energy Program Alloy Development for Irradiation Performance Reference Heat.

An equation of the form of the universal slopes equation was fit to the data from the unirradiated specimens resulting in the following equation:

$$\Delta\varepsilon_T = 2\frac{\sigma_u}{E} N_f^{-0.12} + D^{0.5} N_f^{-0.5} \qquad (1)$$

where

E = Young's modulus,

σ_u = ultimate tensile strength,

D = ductility = $\ln \frac{1}{1 - RA}$,

RA = reduction of area,

N_f = number of cycles to failure,

$\Delta\varepsilon_T$ = total strain range.

Using the tensile properties of another heat of 20%-cold worked type 316 stainless steel irradiated in HFIR,[3] this equation was used to estimate the fatigue life of the irradiated specimens. The curve plotted was based on material irradiated to a fluence of 2.1×10^{26} n/m^2 (E > 0.1 MeV) exhibiting σ_u = 613 MPa and RA =30%. However, this curve significantly overpredicts fatigue life. In order to predict the observed cyclic life, a reduction of area of only 15% must be used in Eq. (1).

The failure of a simple power law equation of the form of the universal slopes equation to predict cyclic life of irradiated material containing helium is not unexpected. The mechanism of reduction in cyclic life is not entirely manifested through ductility. Mechanisms such as migration of helium to grain boundaries aided by cyclic dislocation motion may contribute to degradation of fatigue life but not to reduction of tensile ductility.

Conclusions

Considering the large scatter in irradiated specimen data, it is believed that it is premature to use one of the standard models to estimate fatigue life at the present time. Using a factor of 3 to 10 reduction in life for 20%-cold-worked type 316 stainless steel at 430°C irradiated to 2×10^{26} n/m^2 (E > 0.1 Mev) and containing 200-900 appm He should be used as a guide.

References

1. J. M. Beeston and C. R. Brinkman, Irradiation Effects on Structural Alloys for Nuclear Reactor Applications, ASTM STP 484, American Society for Testing and Materials, Philadelphia, PA, 1970, pp. 419-50.

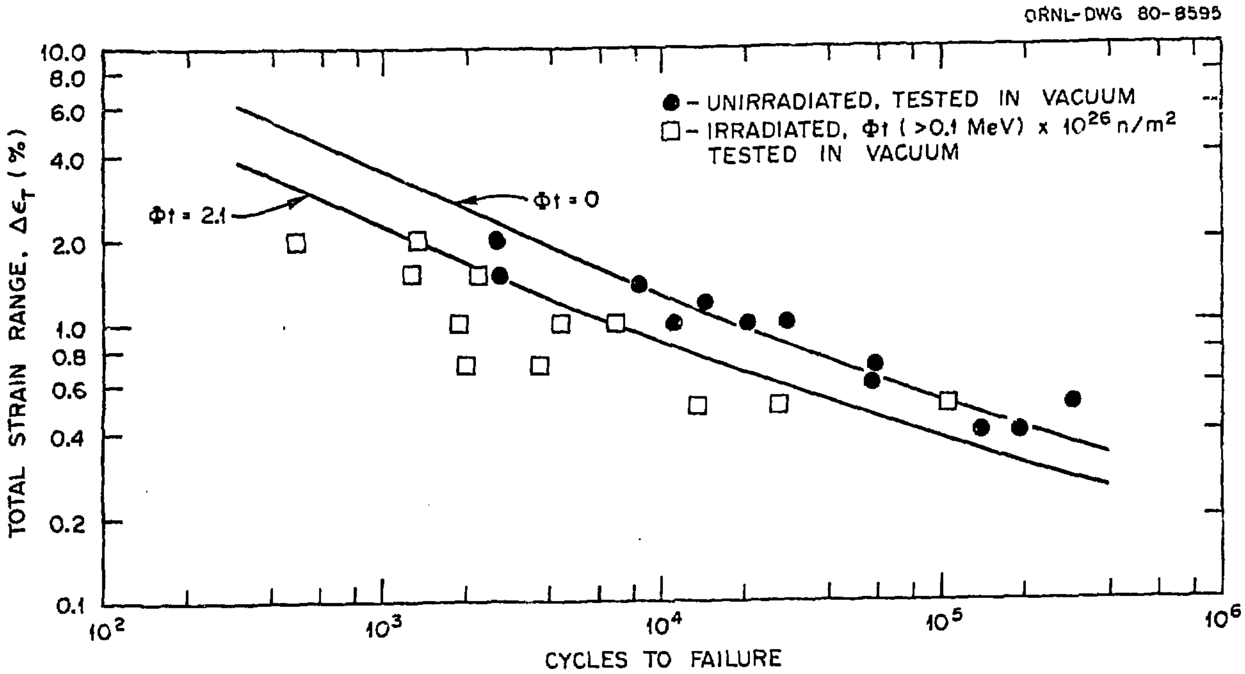
2. M. L. Grossbeck and M. J. Kania, ADIP Program Quart. Prog. Rep. May 1979, DOE/ET/0058/2, pp. 20-35.

3. M. L. Grossbeck and P. J. Maziasz, J. Nucl. Mater. 85 & 86, 883 (1979).

Table 1. Results of Fatigue Tests on Unirradiated and Irradiated Specimens of 20%-Cold-Worked Type 316 Stainless Steel

Specimen	Fluence (>0.1 Mev) (n/m^2)	Helium (at. ppm)	dpa	Total Strain Range (%)	Cycles To Failure	Cycles To Crack	Life Before Crack Initiation (%)
G6	0			2.0	2,550	2,320	91
A96	0			1.5	2,602	2,530	97
G28	0			1.4	8,295	6,920	83
G35	0			1.2	14,250	14,150	99
A68	0			1.0	28,470	17,100	60
G33	0			1.0	11,031	10,060	91
G8	0			1.0	20,400	20,130	99
G26	0			0.70	59,001	56,580	96
G7	0			0.60	57,668	48,680	84
A56	0			0.50	>293,826		
G10	0			0.40	138,692	135,600	98
G18	0			0.40	193,120		
A39	0.85×10^{26}	250	6.6	1.5	1,272	1,080	85
A23	0.85	250	6.6	1.0	1,881	1,300	69
G71	0.85	250	6.6	0.50	105,097		
A37	1.2	440	9.2	2.0	1,360	450	33
A63	1.2	440	9.2	1.0	6,934	6,160	89
A64	1.2	440	9.2	0.70	3,616	2,350	65
A22	1.4	530	11	1.5	2,220	1,760	79
A2	1.4	530	11	0.50	13,330	7,120	53
A8	1.6	660	12	0.70	1,940	1,550	80
A5	1.9	860	15	2.0	483	400	83
A6	1.9	860	15	1.0	4,210	2,900	69
A7	1.9	830	15	0.50	26,175	7,000	27

Fig. 1. Total Strain Range Versus Cycles to Failure for 20%-Cold-Worked Type 316 Stainless Steel Irradiated to 7-15 dpa and Containing 200-900 appm He Tested at 430°C in a Vacuum.


ORNL-DWG 80-8595
TOTAL STRAIN RANGE, $\Delta\epsilon_T$ (%)
10.0
8.0
6.0
4.0
2.0
1.0
0.8
0.6
0.4
0.2
0.1
10^2
10^3
10^4
10^5
10^6
CYCLES TO FAILURE
● – UNIRRADIATED, TESTED IN VACUUM
□ – IRRADIATED, Φt (>0.1 MeV) x 10^{26} n/m^2 TESTED IN VACUUM
Φt = 0
Φt = 2.1