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CONF-811831--28

# HIGH-TEMPERATURE FATIGUE LIFE OF TYPE 316 STAINLESS STEEL CONTAINING IRRADIATION INDUCED HELIUM*

MASTER

M. L. Grossbeck and K. C. Liu
Metals and Ceramics Division, Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830

Specimens of 20%-cold-worked AISI type 316 stainless steel were irradiated in the High Flux Isotope Reactor (HFIR) at 550°C to a maximum damage level of 15 dpa and a transmutation produced helium level of 820 at. ppm. Fully reversed strain controlled fatigue tests were performed in a vacuum at 550°C. No significant effect of the irradiation on low-cycle fatigue life was observed; however, the strain range of the $10^7$ cycle endurance limit decreased from 0.35 to 0.30%. The relation between total strain range and number of cycles to failure was found to be $\Delta\epsilon_T = 0.02\ N_f^{-0.12} + N_f^{-0.6}$ for $N_f < 10^7$ cycles.

## INTRODUCTION

Since almost all conceptual designs of tokamak fusion reactors employ cyclic operation, the resulting thermal stresses are cause for concern about fatigue. In addition to the presence of an intense heat flux, structures close to the plasma such as the first wall will experience a high flux of high energy (up to 14.1 MeV) neutrons. In addition to atomic displacements, such high energy neutrons will result in the production of hydrogen and helium through (n,p) and (n,α) reactions. Although hydrogen diffuses rapidly and is not normally a concern in austenitic stainless steels, helium is insoluble and is known to segregate to sinks such as grain boundaries. It is for these reasons and the fact that AISI type 316 stainless steel (316 SS) is a candidate first-wall material that the effect of fatigue on 316 SS irradiated to induce transmutation helium was investigated.

A previous study on material irradiated and tested at 430°C demonstrated a reduction in fatigue life by a factor of 3–10 for material irradiated to a displacement damage level as high as 15 dpa and a helium content of 800 at. ppm [1,2]. The purpose of the present study is to extend the temperature to 550°C.

## EXPERIMENTAL PROCEDURE

### Specimen Preparation

Specimens were prepared from a reference heat (X15893) of AISI type 316 stainless steel being used in the U.S. Fusion Materials Program. The composition is given in Table I. Following a vacuum anneal at 1050°C for 1 h the material was cold swaged to 20% reduction in area. This treatment resulted in an average grain size of 40 μm. The resulting 6.48 mm rods were machined into specimens with an hourglass gage section 3.18 mm in diameter. The specimen geometry is shown in Fig. 1.

### Irradiation

The technique of introducing helium through nuclear transmutation applies to nickel-containing alloys. Through irradiation in a mixed spectrum fission reactor, atomic displacement damage is accomplished by the fast portion of the spectrum and helium formation through a series of two thermal neutron absorptions beginning with $^{58}Ni$: $^{58}Ni(n,\gamma)^{59}Ni$ and $^{59}Ni(n,\alpha)^{56}Fe$ which deposit helium homogeneously throughout the alloy. The irradiation was done in the High Flux Isotope Reactor (HFIR) for which both the fast and thermal fluxes exceed $10^{19}$ n/(m²-s).

Table I. Composition of AISI Type 316 Stainless Steel Used for the Fatigue Study

| | |
|---|---|
| Cr | 17.28% |
| Mn | 1.70 |
| Ni | 12.44 |
| Mo | 2.10 |
| Co | 0.3 |
| Cu | 0.3 |
| Si | 0.67 |
| Nb | <0.05 |
| Ta | <0.05 |
| Ti | <0.05 |
| B | 4 ppm |
| C | 613 ppm |
| S | 179 ppm |
| P | 370 ppm |

Specimens were arranged ten per irradiation capsule along the longitudinal axis. Figure 1 shows the positioning of a specimen surrounded by a helium gas gap to control radial heat conduction, thus providing the desired elevated temperature through nuclear heating. Low melting metals and alloys and silicon carbide were used as temperature indicators as described in previous reports [2–4]. The melt wire materials used were Cu–30.7 Mg, Mg–23.5 Ni, Al–33 Cu, Al–11.7 Si, and Zn. The irradiation temperature was determined to be 550 ± 25°C which was then used as the test temperature.

Irradiation and test parameters are given in Table II. Damage levels were calculated using the method recommended by the IAEA working group [5] based on previous dosimetry measurements, and helium levels were calculated from a relation based on experimental data [6].

*Research sponsored by the Office of Fusion Energy, U.S. Department of Energy, under Contract No. W-7405-eng-26 with the Union Carbide Corporation.

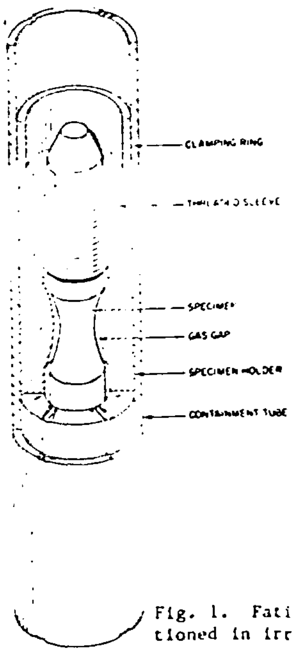


Fig. 1. Fatigue specimens positioned in irradiation capsule.

## Fatigue Testing

The tests were performed on a servo-hydraulic closed-loop controlled testing system installed in a radiation hot cell. The system has a four-column load frame capable of 220 kN (50,000 lb). It is equipped with an ultrahigh vacuum system pumped by a turbomolecular pump capable of pressures of $10^{-6}$–$10^{-4}$ MPa during elevated temperature testing. Specimen heating is accomplished by RF-induction with a load coil surrounding the specimen. Strain is measured by a diametral extensometer which fits between two windings of the load coil.

Tests were performed at the irradiation temperature of 550°C. Specimens were subjected to a reversed triangular strain versus time program beginning with compression at a strain rate of $4 \times 10^{-3}$ $s^{-1}$. For low-cycle fatigue ($\Delta\varepsilon_t \geq$ 0.5%), tests were controlled on the basis of axial strain calculated from diametral strain, measured directly at the minimum gage section, through a strain computer. For high-cycle tests, the same strain control was used until a stable hysteresis loop was achieved, at which time control was shifted to load. At the same time the frequency was increased by a factor of 10 to reduce the test duration. Specimens were cycled to complete separation in order to perform fractography, except in cases where an apparent endurance limit was observed. All specimens, both irradiated and unirradiated, were loaded remotely using the same procedure in order to avoid differences in alignment.

## RESULTS

The alloy exhibited initial cyclic hardening followed by a small amount of cyclic softening before a stable hysteresis loop was established. A cyclic stress-strain curve shown in Fig. 2 was plotted using the stress ranges at half the number of cycles to failure. For low strains where deformation is nearly completely elastic, the irradiated material behaves like the unirradiated material. For higher strains the unirradiated material exhibits a significantly higher cyclic strength than the irradiated materials. The lower cyclic strength in the irradiated condition is opposite the behavior exhibited by similar material irradiated and tested at 430°C [2].

Table II. Irradiation and Test Parameters

| Specimen | Irradiation Temperature (°C) | Test Temperature (°C) | Fluence > 0.1 MeV | dpa | Helium | Total Strain Range | Cycles to Failure $N_f$ | Cycles to Crack | Maximum Stress $\Delta\sigma/2$ at $N_f/2$ (mPa) |
|---|---|---|---|---|---|---|---|---|---|
| G38 | 550 | 550 | 0 | | | 2.0 | 2,286 | 2,080 | 555 |
| G41 | 550 | 550 | 0 | | | 1.5 | 3,043 | | 351 |
| G50 | 550 | 550 | 0 | | | 1.2 | 9,456 | | 496 |
| G51 | 550 | 550 | 0 | | | 0.70 | 56,692 | | 455 |
| G43 | 550 | 550 | 0 | | | 0.42 | 3,125,650 | | 317 |
| G39 | 550 | 550 | 0 | | | 0.30 | >11,359,000 | | 227 |
| G42 | 550 | 550 | 0 | | | 0.30 | >10,643,500 | | |
| A86 | 550 | 550 | 1.9 | 14 | 780 | 2.0 | 1,256 | | 440 |
| A74 | 550 | 550 | 1.2 | 9.0 | 400 | 1.8 | 2,142 | | 400 |
| A87 | 550 | 550 | 1.9 | 15 | 820 | 1.0 | 10,690 | | 365 |
| A76 | 550 | 550 | 1.2 | 9.0 | 400 | 0.87 | 31,595 | 31,000 | 337 |
| A85 | 550 | 550 | 1.6 | 12 | 620 | 0.50 | 143,297 | 134,000 | 290 |
| A95 | 550 | 550 | 1.1 | 9.1 | 410 | 0.42 | 288,410 | 284,300 | 317 |
| A88 | 550 | 550 | 1.9 | 14 | 780 | 0.35 | 1,800,000 | | 269 |
| A75 | 550 | 550 | 1.2 | 9.2 | 420 | 0.30 | >10,437,200 | | 227 |

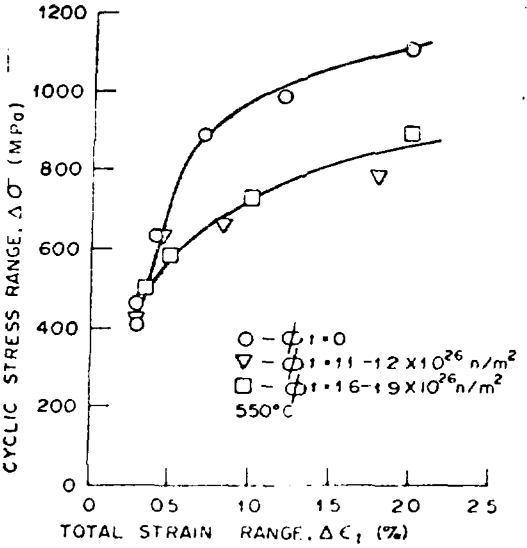


Fig. 2. Cyclic stress-strain curves for HFIR-irradiated and unirradiated 20%-cold-worked AISI type 316 stainless steel. Each point represents an individual specimen. Test temperature = irradiation temperature = 550°C.

The results of the fatigue tests are presented in Table II and plotted on a $\Delta\epsilon_T$ versus $N_f$ curve in Fig. 3. In the low-cycle regime, although there is some hint of a reduction in fatigue life at the highest fluence level, there is not sufficient evidence to establish any difference between irradiated and unirradiated material. All the data are found to fit well on a single curve given by

$$\Delta\epsilon_T = 0.02\ N_f^{-0.12} + N_f^{-0.6}$$

where

$\Delta\epsilon_T$ = total strain range,
$N_f$ = cycles to failure.

The high-cycle tests were discontinued at approximately $10^7$ cycles which was considered to be an apparent endurance limit. This $10^7$ cycle endurance limit was observed at $\Delta\epsilon_T = 0.35\%$ for the unirradiated condition and $\Delta\epsilon_T = 0.30\%$ for the irradiated condition.

The fracture surfaces were studied by scanning electron microscopy (SEM) to help identify the fracture mechanism. In contrast to the behavior at 430°C, all the specimens fractured with a "slant" fracture surface. However, the morphology of the fracture surfaces themselves exhibited many similar features and trends. For material in the unirradiated condition, the surfaces showed almost exclusively ductile rupture. In the irradiated case, ductile rupture still prevailed, but the fracture surfaces showed

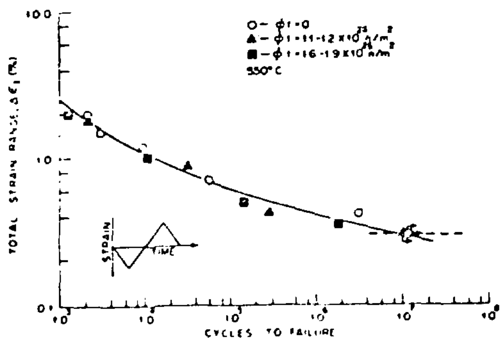


Fig. 3. Total strain range as a function of cycles to failure for HFIR-irradiated (9–15 dpa, 400–820 at. ppm He) and unirradiated 20%-cold-worked AISI type 316 stainless steel.

reduced ductility. In addition, intragranular fracture resembling cleavage appeared at a strain range of 0.42% in irradiated material (Fig. 4). This phenomenon was also observed at 430°C where a much clearer trend was demonstrated. The phenomenon appears to be only sporadic at 550°C.

DISCUSSION

The cyclic hardening curve in Fig. 2 illustrates the effect of irradiation on cyclic hardening. In contrast to the behavior of material irradiated and tested at 430°C, the irradiated material exhibited a lower level of cyclic hardening probably due to irradiation assisted recovery [7] and coarsening of the microstructure with irradiation at high temperatures.

The fatigue life of irradiated material is influenced little if any at 550°C (Fig. 3). This behavior contrasts with the results at 430°C where a reduction in fatigue life by a factor of 3–10 was observed upon irradiation to similar fluence levels [1,2]. The absence of a detrimental effect is somewhat unexpected due to the high concentrations of helium in the irradiated specimens. However, since 550°C is still somewhat low for helium embrittlement, it cannot be determined if there will be a degradation of fatigue life at high helium concentrations or if the presence of helium retards the progression of fatigue damage. The lower cyclic hardening in irradiated material does not support the mechanism of dislocation pinning by helium [8]. It is possible that the degradation in fatigue life observed at 430°C results from a precipitation phenomenon rather than helium. Further study is being conducted to determine the reason for this effect.

The fracture surfaces reveal a highly ductile failure mode which could account for the good performance in low-cycle fatigue. The intragranular cleavage-like morphology observed at

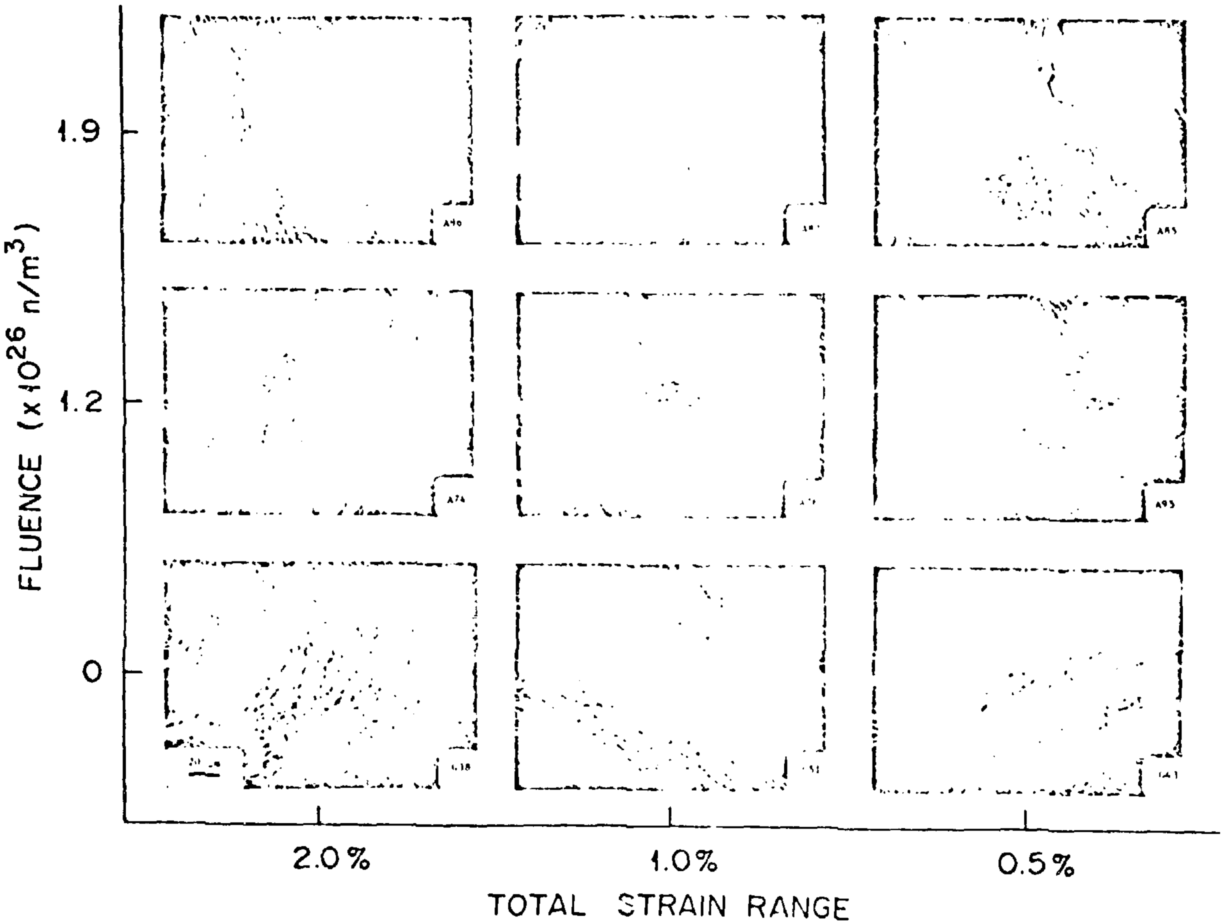


Fig. 4. Fluence versus total strain range (duration of test increases to the right) showing representative portions of the fracture surfaces for type 316 stainless steel irradiated and tested at 550°C. Photographs have been shifted slightly to form straight rows and columns.

$\Delta\varepsilon_T$ = 0.42% might be expected to be associated with premature failure, but this is not observed. This mechanism is likely to be associated with precipitation on the slip bands created by preirradiation cold work [2], but since it does not adversely affect strength, (the cyclic strength is significantly above the curve in Fig. 2 at $\Delta\varepsilon_T$ = 0.42%, $\Delta\sigma_T$ = 317 MPa), its effect on high-cycle fatigue life is minimal.

## CONCLUSIONS

For the 20%-cold-worked AISI type 316 stainless steels irradiated to 9–15 dpa containing 400–820 at. ppm He irradiated and tested at 550°C:

1. The fatigue life was not significantly affected by the irradiation.
2. The cyclic strength was reduced by irradiation in the HFIR .

3. A $10^7$ endurance limit of 0.30% for HFIR-irradiated material and 0.35% for unirradiated material was observed.

4. A transgranular cleavage-like fracture morphology was observed in irradiated material for a strain range of 0.42%.

## ACKNOWLEDGMENTS

*The authors wish to thank C. O. Stevens and* L. G. Shrader for performing the tests and R. W. Swindeman and R. L. Klueh for reviewing the manuscript. The assistance of F. A. Scarboro in editing and typing the manuscript is gratefully appreciated.

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