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Bend-fatigue properties of 590 MeV proton irradiated JPCA and 316F SS

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Abstract

A beam window of a spallation target will be subjected to proton/neutron irradiation, pressure wave and thermal stresses accompanied by high-energy proton beam injection. To obtain irradiation data, the SINQ target irradiation program (STIP) was initiated in 1996 at PSI. JAERI takes part in STIP and conducted the post-irradiation examination of JPCA, 316F. Irradiation conditions of JAERI specimens were as follows: proton energy was 590 MeV. Irradiation temperature ranged from 135 to 360 °C and irradiation dose from 6.3 to 12.5 dpa. The fatigue life of irradiated specimens is almost the same as that of unirradiated specimens. On the other hand, fracture surfaces varied with irradiation conditions. Specimens irradiated at low temperature fractured in a ductile manner. However, intergranular fractured surfaces were observed for 316F irradiated up to 12.5 dpa at 360 °C.

1. Introduction

In several institutes, research and development for an accelerator-driven spallation neutron source has been undertaken. Spallation neutron sources are composed of a high-intense proton accelerator and a heavy metal target. A beam window of a target will be subjected to proton/neutron irradiation, pressure wave and thermal stresses accompanied by high-energy proton beam injection. High-energy proton/neutron irradiation is characterized by high displacement energy and high gas production rates. Gas production rates of helium and hydrogen are estimated to be 70 and 500 appm/dpa, respectively. The effects of the gases on the mechanical properties of target materials are not fully understood. The thermal stresses impose cyclic bending stress on the target materials.

To obtain the irradiation data, the SINQ target irradiation program (STIP) was initiated in 1996 at Paul Scherrer Institute (PSI) and has been progressing [1]. JAERI takes part in STIP and conducted the post irradiation examination of Japanese Primary Candidate Alloy (JPCA), 316F SS and F82H. Examination covered tensile tests, bending fatigue tests, scanning electron microscope (SEM) observation of fracture surfaces, metallurgical observation of microstructure after failure, and measurement of gas production. Our interest is to characterize the effects of proton and neutron radiation on mechanical properties. The irradiation data on JPCA are reported elsewhere [2]. This study includes the results of bend-fatigue tests on JPCA and 316F SS.

2. Experimental details

2.1. Materials and specimens

JPCA is a stainless steel modified by the addition of Ti to AISI type 316 SS in order to improve swelling

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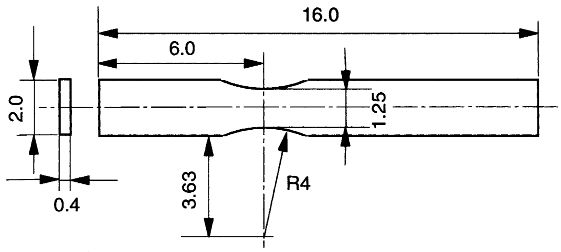

Fig. 1. Test specimen for bend-fatigue tests.

resistance. The chemical composition of JPCA is Fe–14.14Cr–15.87Ni–2.29Mo–1.54Mn–0.22Ti–0.028Co–0.004B–0.058C–0.50Si–0.026P–0.004S–0.003N (wt%). The chemical composition of 316F SS is Fe–16.79Cr–13.95Ni–2.34Mo–0.23Mn–<0.001Co–0.04C–0.04Si–<0.003P–0.002S–0.011N (wt%). The small fatigue specimen used in this study is shown in Fig. 1. The specimen was originally developed at ORNL [3] and modified for STIP at PSI [1]. Specimens were cut from 15 mm thick plates by EDM (Electrical Discharge Machining) and then mechanically polished. After polishing, JPCA and 316F specimens were solution-annealed at 1120 °C for 1 h and 1060 °C for 1 h, respectively. The value of average grain size for JPCA and 316F were 77 and 85 μm, respectively.

2.2. Irradiation

The irradiation was performed at SINQ target in PSI. Proton energy was 590 MeV. Irradiation temperature ranged from 135 to 360 °C and dose from 6.3 to 12.5 dpa. Irradiation temperature ranged because of a change of beam profile. During the first 13-months of the 15 month run, the specimens were irradiated at the lower temperature; during the last two months specimens were irradiated at the higher temperature. Details of irradiation history were reported by PSI [1]. Gas production rates were calculated to be 70 appm helium/dpa and 500 appm hydrogen/dpa. Specimen ID and irradiated conditions are summarized in Table 1.

2.3. Post-irradiation examination

Three JPCA-SA specimens and five 316F-SA specimens were transported to JAERI. All PIE (post-irradiation examination) works were done in the Hot Laboratory at JAERI Tokai. The STIP specimens are very small so that we developed a new fatigue-testing machine with ceramic piezoelectric actuators [4]. Fig. 2 shows the fatigue-testing machine. The specimen is put into the slit of the specimen holder and fixed. Deflection is magnified by the action of the lever and transmitted to the specimen that is clamped by the rollers. Specimens are deflected repeatedly by the cantilever mechanism. The number of cycles to failure was monitored by a change of the direct current from the battery. Bend-fatigue tests were performed under deflection control mode. The deflection of the lever is measured using an eddy-current type displacement sensor. The deflection applied to the specimen can be converted to the strain and the stress by FEM calculations [4]. The results of FEM calculations indicate that the maximum strain is observed slightly to the holder side of the necked sec-

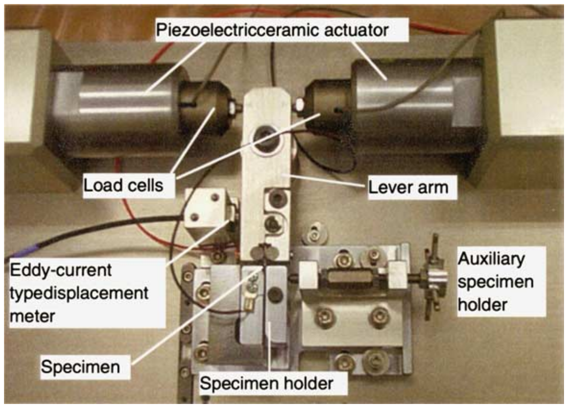

Fig. 2. Photograph of the fatigue-testing machine with piezoelectric ceramic actuators.

Table 1
Irradiation conditions of JPCA-SA and 316F-SA specimens

Specimen I.D.	Irradiation temp. (°C)	dpa	He (appm)	H (appm)
JPCA				
F24	210–245	9.1	637	4550
F26	140–164	6.3	441	3150
F27	140–164	6.3	441	3150
316F				
G31	320–360	12.5	875	6250
G33	320–360	12.5	875	6250
G35	200–240	9.1	637	4550
G36	135–160	6.3	441	3150
G37	135–160	6.3	441	3150

tion. Actually, specimens fractured at the zone. Total strain range is defined as amplitude of the strain at the necked section. The frequency was 26 Hz and its waveform was reversed sine curve. All tests were done in air at room temperature.

SEM (scanning electron microscope, SHIMADZU EPM-810Q) observation was conducted on the fracture surfaces of specimens. Specimens were prepared by depositing a thin film of Au. Accelerating voltage was 20 kV.

3. Results

3.1. JPCA-SA

Fig. 3 shows the results of bend-fatigue tests on unirradiated and irradiated [2] JPCA-SA. The number of irradiated specimens is very limited so that the effect of dpa on the N_f (number of cycles to failure) is not clearly seen. The comparison of unirradiated and irradiated specimens shows that the fatigue life is not changed, irrespective of the irradiation.

SEM photographs of fracture surfaces after fatigue tests are shown in Fig. 4. Fig. 4(a) shows the fracture surfaces of an unirradiated specimen showing a flat transgranular morphology. Fig. 4(b) shows the fracture surface of a specimen irradiated to 6.3 dpa, with the surface showing a transgranular morphology but flatness reduced compared to the unirradiated specimen. There are two data at the same dpa and the fracture surface corresponds to higher stress condition in Fig. 3. Fig. 4(c) shows the fracture surface of a specimen irradiated to 9.1 dpa. This fracture surface shows much finer scale fractures.

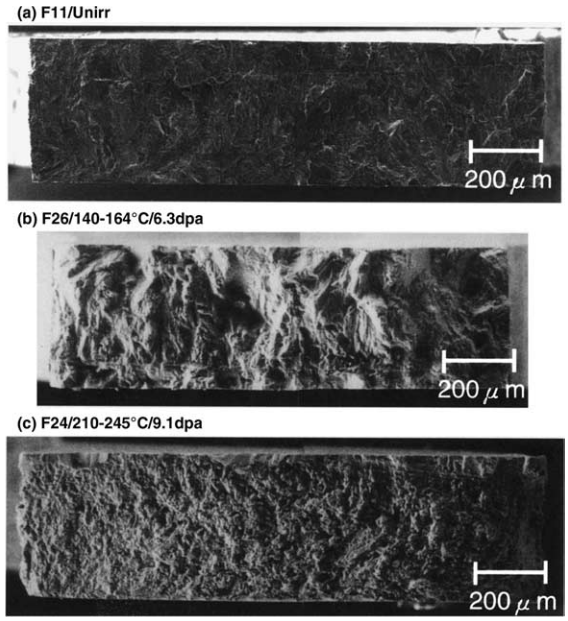

Fig. 4. Fracture surfaces of unirradiated and irradiated JPCA-SA specimens.

3.2. 316F-SA

Fig. 5 shows the results of bend-fatigue tests on 316F-SA. The number of irradiated specimens is only five and scatter of the data is relatively large. The fatigue life of irradiated specimens is almost the same as that of

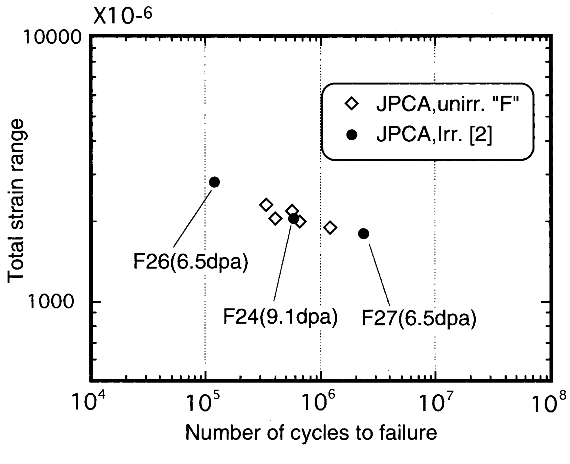

Fig. 3. Fatigue life of unirradiated and irradiated JPCA-SA specimens as the total strain range versus the number of cycles to failure on a log–log scale.

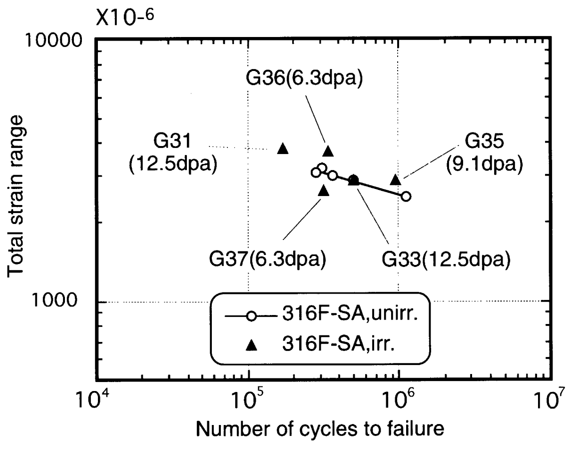

Fig. 5. Fatigue life of unirradiated and irradiated 316F-SA specimens as the total strain range versus the number of cycles to failure on a log–log scale.

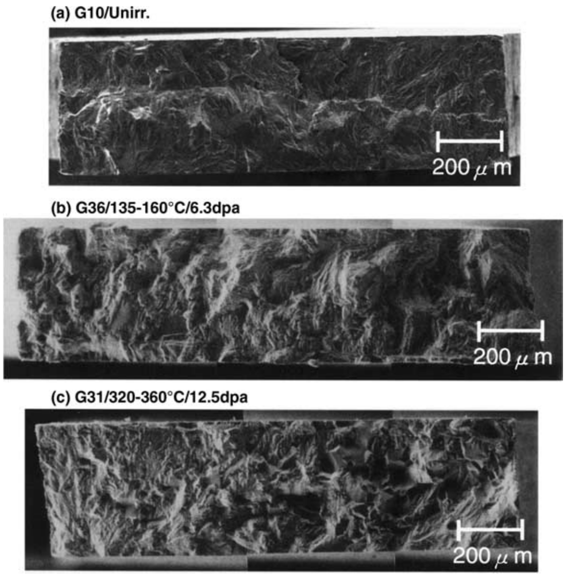

Fig. 6. Fracture surfaces of unirradiated and irradiated 316F-SA specimens.

unirradiated specimens. There is no dose dependence of N_f seen in the results.

Fig. 6 shows SEM photographs of fracture surface after fatigue tests. The fracture surface of an unirradiated specimen shows a flat transgranular morphology as shown in Fig. 6(a). Fig. 6(b) shows the fracture surface of a specimen irradiated to 6.3 dpa, and the surface shows a transgranular morphology but the flatness is reduced in comparison with the unirradiated specimen. Fig. 6(c) shows the fracture surface of a specimen irradiated to 12.5 dpa at 360 °C, where an intergranular fracture surface was observed.

4. Discussion

There are limited data on the fatigue life of irradiated austenitic stainless steels [5–8], with all of the data obtained by axial strain fatigue tests. There are no data on bend-fatigue life of irradiated specimens. However, it is possible to discuss the irradiation effects on fatigue life. Some authors [5–7] report that fatigue life is reduced by irradiation. On the other hand, Puzzolante [8] concluded that there is little or no effect of irradiation on the fatigue life. In this study, little or no change of the fatigue life was observed for the irradiated specimens. In the experimental conditions, gas concentrations do not affect the fatigue properties, because helium atoms are not able to move easily at the low temperature. However, the intergranular fracture surface of the specimen irradiated to 12.5 dpa at 360 °C indicates the possibility of embrittlement of materials at higher temperature irradiation.

Furthermore, the results show no significant difference of fatigue life between the transgranular fractured and the intergranular fractured specimens. The possible reason is as follows: fatigue life may not be strongly affected by the difference of fracture surfaces, in other words, the dominant factor for fatigue life is not crack propagation processes but crack initiation. If these are true, crack initiation is unchanged by irradiation.

The stress distribution obtained by FEM simulation show that the maximum stress is observed at the surface around the edge. Probably crack initiates here and propagate to failure. Though striations are partly seen in the higher magnification micrographs, directions of crack propagation are unknown. Further investigation will be necessary for fracture surface.

5. Conclusion

In STIP JAERI conducted bend-fatigue tests of austenitic stainless steels irradiated at SINQ target 3. The main conclusions are as follows.

(1) Bend-fatigue tests were performed for the irradiated specimens by using a new fatigue-testing machine with piezoelectric ceramics actuators.
(2) Little or no change of the fatigue life was observed for the irradiated JPCA-SA and 316F-SA specimens.
(3) Fracture surfaces varied with irradiation conditions. Specimens irradiated at low temperature showed a transgranular morphology. However, intergranular fracture surfaces were observed for 316F SS irradiated up to 12.5 dpa at 360 °C.

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