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Tensile and transient burst properties of advanced ferritic/martensitic steel claddings after neutron irradiation

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Abstract

The effects of fast neutron irradiation on tensile and transient burst properties of advanced ferritic/martensitic steel claddings for fast breeder reactors were investigated. Specimens were irradiated in the experimental fast reactor JOYO using the material irradiation rig at temperatures between 773 and 1013 K to fast neutron doses ranging from 11 to 102 dpa. The post-irradiation tensile and temperature-transient-to-burst tests were carried out. The results of mechanical tests showed that there was no significant degradation in tensile and transient burst strengths after neutron irradiation below 873 K. This was attributed to grain boundary strengthening caused by precipitates that preferentially formed on prior-austenite grain boundaries. Both strengths at neutron irradiation above about 903 K up to 102 dpa decreased due to radiation enhanced recovery of lath martensite structures and recrystallization.

1. Introduction

Ferritic/martensitic (F/M) steels are expected to be good candidate materials not only for the long life core material of fast reactors (FRs), but also for the blanket materials of fusion reactors because of their superior swelling resistance. Studies of most F/M steels have been focused on their mechanical properties at lower temperatures ($\leqslant$673 K) under neutron irradiation environments. Although it is very important to operate reactors at high temperatures to increase the thermal efficiency in the FRs and fusion reactors, present research efforts focused on behaviors of F/M steels at the higher temperatures and heavy neutron irradiation doses are relatively limited [1–10]. The objective of this study is to evaluate the effect of neutron irradiation on mechanical properties of 11Cr–0.5Mo–2W–V, Nb F/M steel (PNC-FMS) claddings, especially tensile properties and transient burst properties, under high neutron dose and temperature conditions.

2. Experimental procedures

2.1. Materials and irradiation condition

Materials used in this work are 11Cr–0.5Mo–2W–V, Nb F/M steels. Details of the PNC-FMS were reported in Refs. [11,12]. Steel specimens from

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Table 1
Chemical compositions and heat treatment conditions of PNC-FMS claddings (mass %)

Lot	C	Si	Mn	P	S	Ni	Cr	Mo	W	N	Nb	V	Fe
61FS	0.10	0.07	0.54	0.002	0.002	0.32	11.1	0.45	1.89	0.04	0.06	0.21	bal.
61FSF	0.12	0.06	0.69	0.002	0.002	0.82	11.0	0.09	2.11	0.04	0.06	0.20	bal.

Heat treatment conditions:
61FS, Normalized at 1373 K for 10 min and then tempered at 1053 K for 1 h.
61FSF, Normalized at 1333 K for 10 min and then tempered at 1023 K for 10 h.

lots 61FS and 61FSF were prepared. Two lots were treated at different heat treatments. Their chemical compositions and heat treatment conditions are shown in Table 1. There were no significant effects of different heat treatments on mechanical properties [7] and so, in this paper, these two lots were regarded as similarity.

The cladding specimens (6.5 mm outer diameter, 0.47 mm wall thickness and 75 mm length) were irradiated in the experimental fast reactor JOYO using the material irradiation rig for the tensile and temperature-transient-to-burst tests. There were 17 irradiation conditions for temperatures between 773 and 1013 K and a fast neutron dose of 11 to 102 dpa.

2.2. Tensile tests

The tensile test specimen form are shown in Fig. 1, where the irradiated cladding specimen was plugged up both ends and then installed Swagelocks. Tensile tests were carried out in air using a screw-driven tensile testing machine and were conducted at a strain rate of 5.0×10^{-5}/s, which was changed to 1.3×10^{-3}/s after yielding. The test temperatures were 773, 823, 873, 903, 933 and 1013 K corresponding to the irradiation temperatures. Yield strength (YS) was determined as 0.2% offset proof stress.

2.3. Temperature-transient-to-burst tests

The temperature-transient-to-burst tests [8,13] were performed on irradiated cladding specimens. The specimen was internally pressurized by high purity argon gas, and then heated linearly by direct electric current in order to study rupture strength during ramp heating. The temperature was measured by a Type *R* thermocouple. The heating rate was 5 K/s because of the importance of this heating rate during operational transients in the prototype fast breeder reactor MONJU. The axial temperature distribution during the transient heating was confirmed to be within ±25 K in a 20 mm region around the axial center of the specimen. The hoop stress conditions, which were estimated by the thin walled tube approximation, were 49, 98, 120 and 196 MPa.

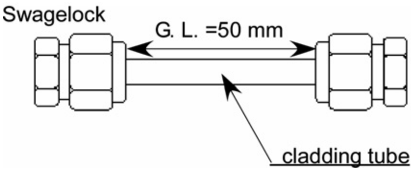

Fig. 1. Schematic drawing of tensile test specimen.

3. Results

3.1. Tensile strength and elongation

Ultimate tensile strength (UTS) and YS of specimens are shown in Fig. 2 as a function of test temperatures. The strengths for thermally aged specimens corresponding to each irradiation time are also shown in Fig. 2. These were calculated using the Larson Miller Parameter (LMP) correlation to compare the effect of the irradiation temperature with the experimental results. Details of LMP and strengths of thermally aged specimens were provided elsewhere [7]. As observed in Fig. 2(a) and (b), UTS and YS after neutron irradiation were nearly equal to those of as-received and thermally aged specimens at temperatures below 873 K. On the other hand, with increasing irradiation temperatures up to 903 and 933 K, the strengths after neutron irradiation were lower than those of as-received and thermally aged specimens, but distinctly lower as the as-received specimens. Finally, when irradiation temperature increased to 1013 K, the strengths were close to those of the thermally aged specimens. Thus, it was suggested that the decrease of strengths at 903 and 933 K were greatly influenced by neutron irradiation apart from the thermal aging effect. However, as discussed later at the higher temperature of 1013 K, these strength reductions were related to recovery and/or recrystallization.

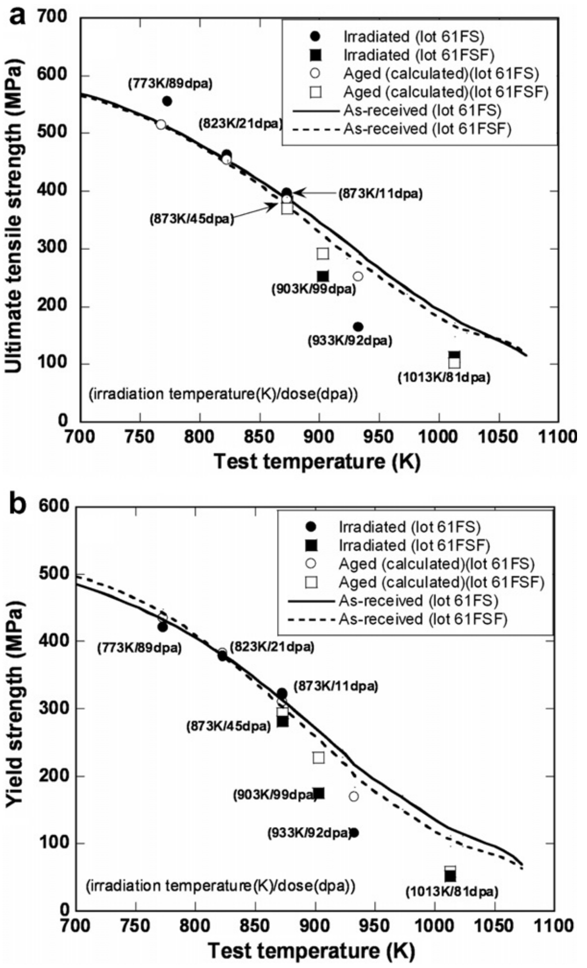

Fig. 2. Tensile strengths of irradiated PNC-FMS claddings: (a) ultimate tensile strength and (b) yield strength.

Fig. 3 shows total elongation before and after neutron irradiation as a function of test equal to irradiation temperature. After irradiation, total elongations obviously increased with temperatures within the scattered total elongation band of as-received specimens, except for specimens irradiated at 773 K to 89 dpa and 873 K to 45 dpa. However, uniform elongations of these irradiated two specimens were at the same level as the as-received specimens.

Degradation of tensile properties during irradiation was confirmed by Kimura et al. [10] for similar 9Cr–2W F/M steels irradiated in FFTF at temperatures above around 700 K up to the lower dose 44 dpa as frequently observed in 9-12Cr MoVNbW F/M steels. Comparing these results to the present ones for PNC-FMS, there was no significant degradation of tensile properties at irradiation temperature between 773 and 873 K up to 89 dpa.

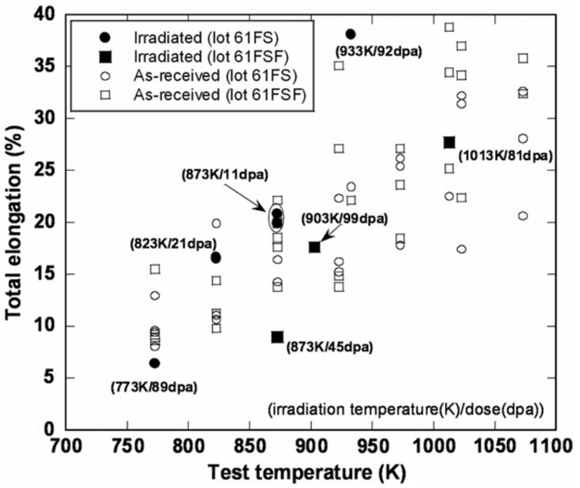

Fig. 3. Total elongation of PNC-FMS claddings before and after neutron irradiation.

3.2. Transient burst strength

The results of temperature-transient-to-burst tests are shown in Fig. 4 as a relationship between hoop stress and failure temperature. It was observed that, at neutron irradiation temperatures below 853 K, the failure temperature (transient burst strength) before and after irradiation with decreasing hoop stress in a similar manner. However, above 943 K the transient burst strengths were shifted to lower values than those of as-received specimens. This suggested that the decrease in transient burst strength would be attributed to effects of neutron irradiation

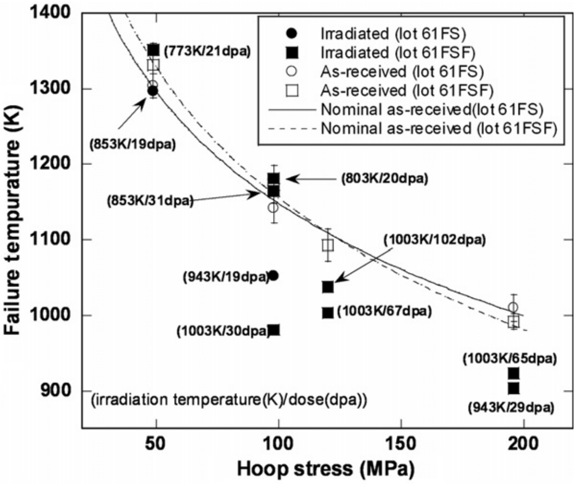

Fig. 4. Relationship between hoop stress and failure temperature of irradiated PNC-FMS claddings. The bar for as-received data shows the standard deviation.

and/or thermal aging according to the behaviors of tensile strengths at the same temperatures.

4. Discussion

As shown in the previous section, the tensile and transient burst strengths decreased as compared with that of as-received specimens at neutron irradiation temperatures above 903 K. To investigate the cause of these strength degradations, transmission electron microscopy observations were performed for PNC-FMS cladding (lot 61FS) irradiated in the FFTF/MOTA at temperatures between 823 and 943 K to around 100 dpa, corresponding to those conditions for tensile and transient burst specimens [14]. Fig. 5 shows typical martensite lath and prior-austenite grain (PAG) boundary microstructures which included a precipitate distribution. The microstructure of the as-received specimens consisted of martensite lath (the average lath width was estimated at 0.3–0.4 μm) in which dislocations were distributed with high density and the precipitates formed on PAG and lath boundaries (Fig. 5(a)). It was clearly observed that most of the PAG boundaries were covered with carbide precipitates ($M_{23}C_6$ type carbide) after neutron irradiation at 823 K to 97 dpa (Fig. 5(b)). Furthermore, precipitates with blocky features (indicated by the arrows in Fig. 5(c)) on the PAG boundaries were observed at higher irradiation temperature of 878 K to 102 dpa (Fig. 5(c)). The lath structures in both irradiated specimens were slightly recovered but no significant change of lath width was recognized. These microstructures correspond to irradiation conditions, where tensile and transient burst strengths were at the same level as those of as-received specimens and total elongations decreased. These observations indicate that the precipitates formed on PAG boundaries significantly contribute to grain boundary strengthening. Likewise, it is suggested that the degradation of total elongation is associated with the significant grain boundary embrittlement with reduction of ductile fracture stress when the PAG boundaries are continuously decorated with precipitates (see the data of 773 K/89 dpa and 873 K/45 dpa).

As shown above, specimens irradiated above 903 K exhibited decreased tensile and transient burst strengths decreased. Fig. 5(d) shows a typical microstructure corresponding to neutron irradiation conditions, where these strengths significantly decreased. A recovery of martensite lath structures and recrystallization has occurred, in which the structures consist of subgrains and recrystallized grains with newly formed precipitates. These recovery and recrystallization were also occurred in commercial HT9 irradiated at 873 K to 34 dpa [15]. Therefore, it is suggested that these microstructural changes lead to a decrease in strength. Furthermore, with increasing irradiation temperature to 1013 K, recovery of lath martensite and/or recrystallization progressed, caused by thermal aging rather than the neutron irradiation effects so that the tensile strengths of the thermally aged and neutron irradiated specimens decreased to nearly equal strength levels. Thus, it has been clarified that the precipitation distribution on PAG boundaries and the lath structural stability play important roles for tensile and transient burst strengths under higher irradiation temperature conditions. However, coarse precipitate formation on PAG boundaries at higher doses reduces tensile ductility.

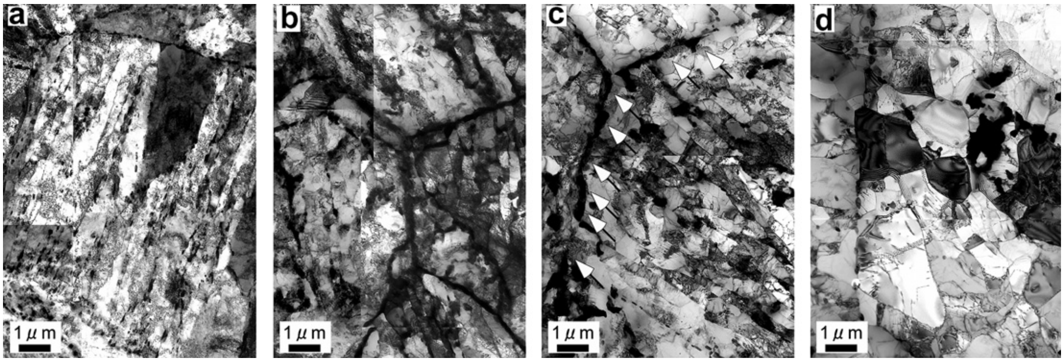

Fig. 5. TEM micrographs of PNC-FMS cladding (lot 61FS): (a) as-received specimen and following FFTE/MOTA irradiation at (b) 823 K to 97 dpa (c) 878 K to102 dpa and (d) 948 K to 103 dpa.

5. Conclusion

Post-irradiation tensile and temperature-transient-to-burst tests were conducted on PNC-FMS claddings. The results are summarized as follows:

(1) After neutron irradiation below about 873 K, tensile and transient burst strengths were at the same strength level as as-received specimens and precipitates were preferentially formed on PAG boundaries.
(2) After neutron irradiation above 903 K, these strengths became lower than those of as-received specimens and with further increasing temperature to 1013 K the tensile strengths were close to strength values of the thermally aged specimens. In these higher temperature ranges, the lath martensite structures were recovered and recrystallized.
(3) It has been clarified that the precipitation distribution on PAG boundaries and the lath structural stability play important roles for tensile and transient burst strengths under higher irradiation temperature conditions. There, however, reduces tensile ductility at higher doses.

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