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ScienceDirect
Journal of Nuclear Materials 367–370 (2007) 494–499
journal of nuclear materials
www.elsevier.com/locate/jnucmat

Effects of irradiation on mechanical properties of HIP-bonded reduced-activation ferritic/martensitic steel F82H first wall

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Abstract

HIP-bonded regions in the first wall of a fusion blanket are subjected to intense neutron irradiation. The purpose of this study is to investigate the influence of radiation damage on the tensile properties of the HIP-bonded regions. Tensile tests have been performed on specimens taken from a HIP-bonded mock-up structure, made to simulate the different fabrication processes. The neutron irradiation was carried out at about 423 K and 523 K to doses up to about 2 dpa. The tensile tests were performed at room temperature, irradiation temperatures and at 623 K. The main results are as follows: (1) Before irradiation, the tensile properties in the HIP-interface were equivalent to those of the matrix region. (2) Rupture did not occur at the HIP-interface of irradiated material. (3) The tensile properties in irradiated material were not notably affected due to manufacturing/fabricating histories. (4) Changes in properties produced by irradiation at 423 K show significant recovery for a test temperature of 673 K.

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1. Objective

The blanket is one of the plasma facing components of a fusion reactor. The first wall, which is a structural part of the blanket, may be fabricated by hot isostatic pressing (HIP) bonding method. F82H steel, a reduced-activation ferritic steel, is regarded as the primary candidate material for first wall.

In general, the properties of first wall materials are degraded due to the exposure to high neutron fluxes for long times. Consequently, it is thought that the integrity of the HIP-bonded region may also be degraded. The first wall is composed of plates and cooling channels, each manufactured by different methods. In addition, the plates and cooling

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doi:10.1016/j.jnucmat.2007.03.011

channels are also subjected to various heat treatment histories in the fabrication process of the first wall. Differences in the manufacturing procedure and/or heat treatment history change the initial microstructure of the material so it is possible that the response of the mechanical properties after irradiation is different from that of as-received material.

In this paper, the influence of neutron irradiation on the mechanical properties in the first wall is discussed for an irradiation temperature range in which significant radiation hardening occurs.

2. Experimental

This study utilized a partial mock-up of the first wall fabricated in a previous study [1]. Plates and cooling channels used for fabrication of the mock-up fell into the chemical composition range designed for the IEA steel F82H [2]. Table 1 shows the heat treatment histories for the cooling channels during their manufacturing and the fabrication process for the mock-up. The heat treatment history of the plate is equivalent to that of the IEA-F82H steel in its manufacturing, and the heat treatment history in the fabrication process of the mock-up is the same as for the plate.

Small tensile specimen, type SS-3, were utilized for the tests. The sheet specimen has a 7.62 mm long, 1.52 mm wide and 0.76 mm thick gage section. Sampling location of the specimens is shown in Fig. 1. The specimens were sampled from matrix regions (plate region and cooling channel region) and regions where the cooling channels were HIP-bonded. Fig. 2 shows microstructure in the IEA-F82H steel and the matrix regions. The specimens were prepared with a surface finish of #1000–1200. Initial tensile tests were performed on material in unirradiated condition. The test temperatures range from room temperature (RT) to 673 K; the strain rate was $5 \times 10^{-4}\,\mathrm{s}^{-1}$. Neutron irradiations were carried out at irradiation temperatures of 423 K and 523 K to doses up to about 2 dpa. After irradiation, tensile tests were performed at RT, the irradiation temperatures and 673 K. Number of tensile specimens per conditions is shown in Table 2. For the HIP-bonded region, the surface of the fracture region was polished, followed by chemical etching to reveal the HIP boundary. The HIP boundary location was confirmed by optical microscopy.

The neutron irradiation was carried out in the JAEA materials testing reactor (JMTR) of the JAEA-Oarai Institute, and the post-irradiation experiments were performed at the hot laboratory of the institute.

Table 1
Heat treatment history applied to cooling channel for first wall mock-up

Condition	Purpose
Production of channel	
(1) 1083 K for 30 min	Annealing after hot extrusion
(2) 1083 K for 30 min	Annealing after mill pressing
(3) 1083 K for 30 min (two times)	Annealing after cold drawing
(4) 1083 K for 15 min	Annealing after roll forming
(5) 1083 K for 15 min (three times)	Annealing after cold drawing
Fabrication of mock-up	
(6) 993 K for 1 h	Stress relieving
(7) 1273 K for 10 h	Out gassing
(8) 1013 K for 2 h	Tempering
(9) 993 K for 1 h	Post-weld heat treatment
(10) 773 K for 2 h	Degassing
(11) 1313 K for 2 h	HIP treatment
(12) 1013 K for 2 h	Tempering
(13) 993 K for 1 h	Stress relieving

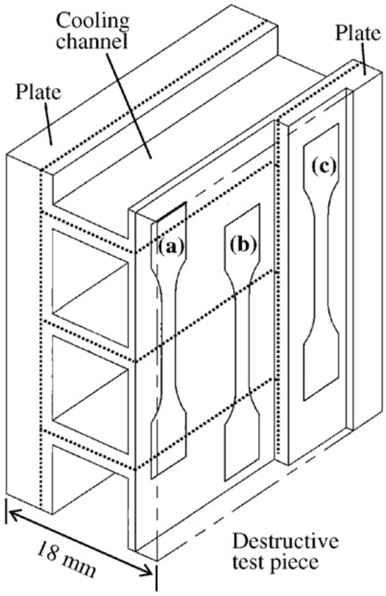


Fig. 1. Sampling location of specimens for tensile tests. The figure shows SS-3-type-tensile specimens sampled from (a) HIP-bonded region, (b) matrix region of channel and (c) matrix region of plate, in first wall mock-up. Broken lines in the figure indicate HIP boundaries.

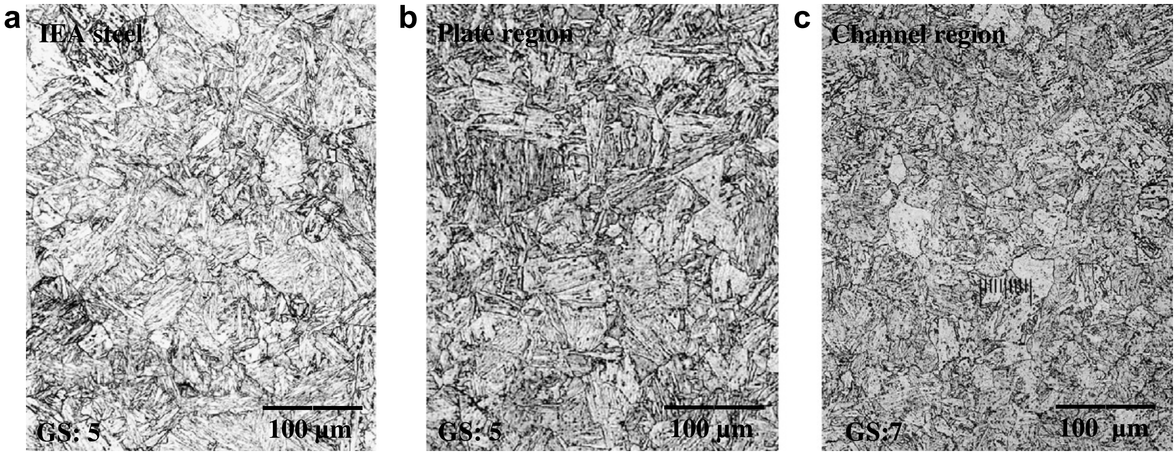


Fig. 2. Microstructures in (a) IEA-F82H steel, (b) plate region and (c) cooling channel region, before irradiation. Although the grain size of the channel is somewhat finer than that of the other material, it seems that no significant difference can confirm within OM observation.

Table 2
Number of tensile specimens per conditions

Test temperature (K)	HIP-bonded region	Matrix region of channel	Matrix region of plate
RT	Unirradiated: One*	Unirradiated: Two	Unirradiated: –
	423 K Irradiated: One	423 K Irradiated: One	432 K Irradiated: One
	523 K Irradiated: One	523 K Irradiated: One	523 K Irradiated: One
423	Unirradiated: –	Unirradiated: –	Unirradiated: –
	423 K Irradiated: One	423 K Irradiated: One	432 K Irradiated: One
	523 K Irradiated: –	523 K Irradiated: –	523 K Irradiated: –
473	Unirradiated: One*	Unirradiated: Two	Unirradiated: –
	423 K Irradiated: –	423 K Irradiated: –	423 K Irradiated: –
	523 K Irradiated: –	523 K Irradiated: –	523 K Irradiated: –
523	Unirradiated: –	Unirradiated: –	Unirradiated: –
	423 K Irradiated: –	423 K Irradiated: –	423 K Irradiated: –
	523 K Irradiated: One	523 K Irradiated: One	523 K Irradiated: One
673	Unirradiated: One*	Unirradiated: Two	Unirradiated: –
	423 K Irradiated: One	423 K Irradiated: One	423 K Irradiated: One
	523 K Irradiated: One	523 K Irradiated: One	523 K Irradiated: One

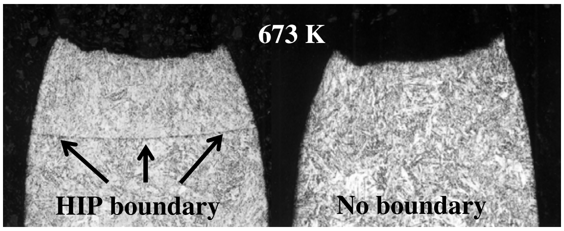
Number with asterisk means that the test was done up to rupture at HIP-interface so that only one of the tested specimens could be used as the tensile properties data in the HIP-interface.

3. Result and discussion

3.1. Soundness of bonded region before and after irradiation

Fig. 3 shows the tensile properties of the channel before irradiation. Specimens used are (a) of Fig. 1 (HIP-bonded region of channel). For instance, macroscopic picture shows the rupture regions of the specimens tested at 673 K. We judged that the specimens had fractured at the matrix region (Matrix-rupture) when the HIP-interface could be confirmed at the rupture region, and were fractured at the HIP-interface (Interface-rupture) when the HIP-interface could not be confirmed. Open symbols and cross symbols in the figure indicate the cases of matrix-rupture and interface-rupture, respectively. The figure shows that the tensile properties in both cases are equivalent. Consequently, the tensile tests in the unirradiated condition revealed that interface-rupture hardly ever affects the tensile properties of the HIP-bonded region, in the testing temperature range RT to 673 K.

Fig. 4 shows macroscopic pictures containing the fracture part of the HIP-bonded region in two neutron irradiated samples. Fig. 4(a) shows the fracture area at 423 K and (b) at 523 K irradiation and test temperatures. As can be seen from the figure, in



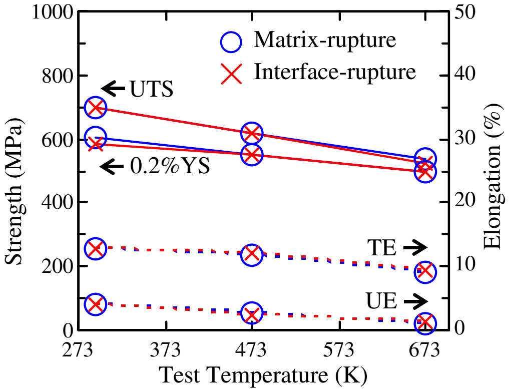
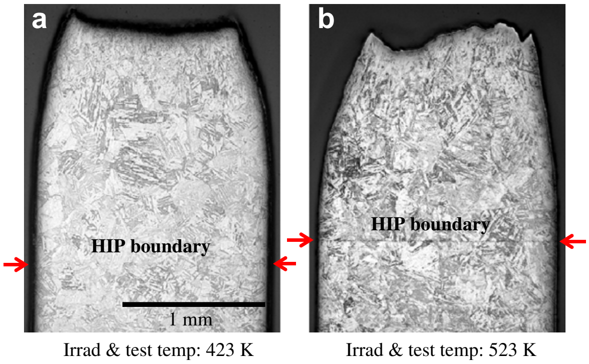


Fig. 3. Tensile properties of matrix region and HIP-interface of channel material before irradiation.



Irrad & test temp: 423 K

Irrad & test temp: 523 K

Fig. 4. Macroscopic views at rupture regions after tensile test for neutron-irradiated bonded region. HIP boundary is visible in both regions.

both cases the HIP-boundaries were located close to the rupture regions. This means that rupture occurred not at the interface but in the matrix region. This shows that the neutron irradiation to doses up to about 2 dpa does not degrade integrity of the HIP-bonded region, relative to changes in the properties of the matrix regions.

3.2. Influence of heat treatment history on irradiation-response

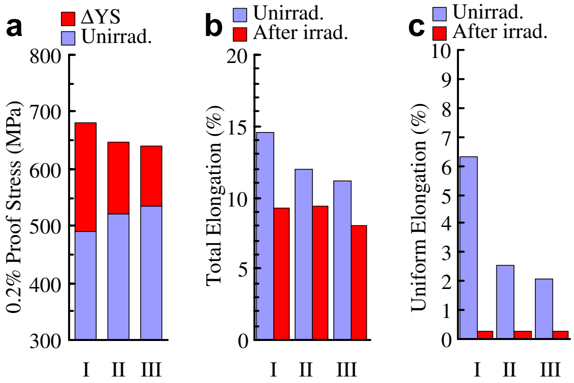


Fig. 5. Changes of strength and elongation in I: IEA-F82H steel [3–5], II: matrix region of plate and III: matrix region of channel, irradiated and tested at about 523 K.

Fig. 5 shows the tensile properties in the plate region (II) and cooling channel region (III) of the mock-up before and after irradiation. For the sake of comparison, the tensile properties of an IEA-F82H steel are also given (I) [3–5]. Irradiation and test temperatures are 523 K. The 0.2% proof stresses are given in (a) of the figure, the total elongations in (b), and the uniform elongations in (c). As shown in Fig. 5(a), the proof stress in the matrix regions of unirradiated material was 520 MPa (II) and 535 MPa (III), respectively whereas for the IEA steel it was 490 MPa (I). After irradiation, the proof stresses increased to 680 MPa (I), 648 MPa (II) and 639 MPa (III), respectively. As can be seen from (a) of the figure, the proof stresses of the matrix regions after the irradiation are lower than that of the IEA steel although they were higher before irradiation. On the other hand, as shown in (b) of the figure, the total elongations in the matrix regions before irradiation were 12% (II) and 11% (III), respectively whereas the IEA steel was 14.5% (I). Although the total elongations in the matrix regions were smaller than that of the IEA steel before irradiation, they were nearly equal after irradiation, at 9.2% (I), 9.4% (II) and 8.0% (III). On the other hand, as shown in (c) of the figure, the uniform elongation in the matrix regions before irradiation were 2.6% (II) and 2.1% (III), respectively whereas the IEA steel was 6.3% (I). Although the uniform elongations in the matrix regions were very small in comparison with that of the IEA steel, their values were the same after irradiation, at 0.3%.

In agreement with in literature data on [4,5] the influence of the difference of tempering conditions on proof stress before and after irradiation, the increment of the proof stress (ΔYS) depends on the difference of dislocation density and/or content of carbon in solution before irradiation. Here, the applied manufacturing methods for the matrix regions, especially for the cooling channels, are quite different from those of the IEA-heat of F82H steel, and subjected to additional heat treatment during the fabrication process of the mock-up (Table 1). Therefore it is very likely that the dislocation density and/or the content of solute carbon in the matrix regions were different from that of the IEA heat of steel before irradiation. That is, there is a possibility that these histories on the matrix regions affect the irradiation response of the tensile properties. However, it is seen that the tensile properties are not significantly degraded in comparison to that of the IEA steel after the irradiation, although the manufacturing methods and/or heat treatment history are different.

3.3. Influence of irradiation temperature on ΔYS

Fig. 6 shows the increase in yield stress, ΔYS, in the matrix regions due to irradiation at 423 K and 523 K for various test temperatures. The test temperatures correspond to the irradiation temperatures, RT and 673 K. Fig. 6(a) and (b) give ΔYSs in the plate region and in the cooling channel region, respectively. In both cases ΔYS after irradiation at 423 K was greater than after irradiation at 523 K, tested at RT and the irradiation temperatures. However, the trend is reversed at a test temperature of 673 K; large recovery was observed for samples irradiated at 423 K compared to samples tested at irradiation temperature and RT. Only little recovery occurred in case of the test samples irradiated at 523 K.

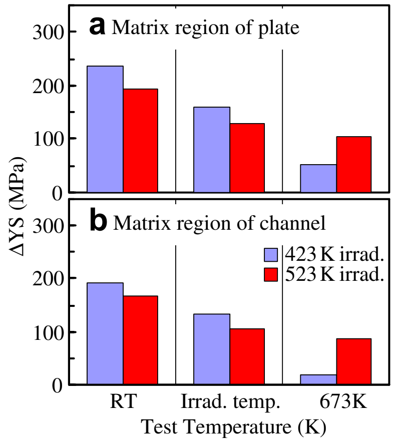


Fig. 6. Difference of ΔYS for 423 K and 523 K irradiations at various test temperatures. ΔYS for 423 K irradiation is higher than for 523 K irradiation, where tested at irradiation temperatures and room temperature. The trend is reversed for 673 K test temperature.

The type of lattice defect formed depends on the irradiation temperature. For instance, irradiation at higher temperature mainly forms dislocation loops, at lower irradiation temperature black dots occur. This difference in lattice damage affects the stability of the damage in its recovery. That is, it can be inferred that the advanced recovery in tests at 673 K was seen for an irradiation temperature of 423 K because lattice damage formed at 423 K was unstable in comparison with that formed at 523 K.

4. Summary

Tensile properties of F82H were examined for unirradiated HIP-bonded and matrix regions, tested at RT to 673 K. Similar material irradiated at about 423 K and 523 K to doses up to about 2 dpa were tensile tested after irradiation, at RT, the irradiation temperatures, and 673 K. The study gave the following results:

1. Tensile properties of the HIP-interface were equivalent to those of the matrix region before irradiation.
2. Rupture did not occur at the HIP-interface after irradiation.
3. Influences of manufacturing method and/or heat treatment history are small in the strength and elongation after irradiation.
4. Tensile tests at 673 K of material irradiated at 423 K showed significant recovery of properties, compared to tests of samples irradiated at 423 K and tested at RT or 423 K.

Acknowledgements

The authors would like to express their sincere appreciation to Drs F. Takada, Y. Kato and the other staff for performing irradiations and post-irradiation experiments, and Drs S. Jitsukawa, K. Nakamura, H. Nakamura and M. Ida for their assistance. We also would like to acknowledge Drs M. Seki and H. Takatsu for their continuous encouragement through this work.

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