Reduced activation Ferritic/Martensitic steel F82H for in-vessel components
-Improvement of irradiation response of toughness and ductility-

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Recent results on the effects of irradiation on mechanical properties of reduced-activation ferritic/martensitic steel, F82H, are described. Irradiation hardening and fracture toughness of F82H steel after irradiation at relative low temperatures below 400°C, were investigated with a focus on changing the fracture toughness transition temperature as a result of several heat treatments. The results revealed that optimization and tightening of the tempering condition improved the irradiation response with respect to toughness and ductility. The impact of irradiation effects on the structural integrity is evaluated and the feasibility of this steel for DEMO application is discussed.

1. Introduction

The reduced activation ferritic/martensitic (RAF/M) steel F82H is recognized to be a leading candidate material for in-vessel components in a future fusion DEMO reactor, as well as that for ITER test blanket modules (TBM) in Japan [1-3]. The service temperature of RAF/M steels for the DEMO is expected to range from 300 to 550°C. The displacement damage level during the DEMO service period is expected to be 150 dpa (displacement per atom). The 14 MeV D–T neutrons produced in fusion systems cause both displacement damage and transmutation products such as He and H atoms in the materials.

Examination of the neutron irradiation response of RAF/M steels has been carried out mainly in JA-US collaborative experiments using the High Flux Isotope Reactor at Oak Ridge National Laboratory. F82H is the reference heat for the collaborative experiments.

Degradation of mechanical properties after irradiation should be suppressed within a range permissible for reactor design. The important issues introduced by irradiation are reductions of elongation, fracture toughness, creep under irradiation and fatigue properties. It has been pointed out that proper control of microstructure before irradiation by appropriate heat treatment enables reduction of irradiation hardening and ductile brittle transition temperature (DBTT). The results of recently completed post-irradiation examination demonstrated a remarkable improvement in the irradiation-induced degradation of fracture toughness after optimizing and tightening the heat treatment condition, as well as by controlling of minor alloying elements like tantalum, nitrogen and titanium. The degradation of fracture toughness was evaluated by the shift of ductile to brittle transition temperature (DBTT-shift). The optimization and tightening of tempering condition are also revealed to be effective for maintaining post-irradiation ductility. DBTT-shift and reduction of ductility by irradiation have been recognized to be critical issues for RAF/M steels; therefore, the beneficial effect of the optimization of tempering condition may be to extend the service conditions of RAF/M steels. In this paper, the current status of development of F82H is reported. Results of fracture toughness, tensile, creep and fatigue properties are introduced focusing on the improvement of the irradiation response of DBTT. The impact on structural integrity is also briefly discussed. Recent developments for the fabrication of components will be introduced.

2. Effect of irradiation on mechanical properties

(i) Heat treatments

Specimens used in this study were basically F82H (Fe-8Cr-2W) martensitic steels. Three types of the F82H specimens were standard F82H-IEA (labeled IEA), F82H-IEA with several heat treatments (Mod1 series) and F82H with 0.1 % tantalum (Mod3).

TABLE I: HEAT TREATMENTS OF F82H STEELS.

ID	Normalizing	Tempering	Heat treatment1	Heat treatment2	Note
IEA	1040°C /40min	750°C /1h	N/A	N/A	2^{nd} 5t heat, IEA round robin test
Mod1A			800°C/0.5h	700°C/10h	Over tempered HAZ
Mod1B			860°C/0.5h	700°C/10h	HAZ over Ac1:820°C
Mod1C			920°C/0.5h	700°C/10h	HAZ over Ac3:910°C
Mod1E	IEA+1100°C/2h +960°C/0.5h (HIP and fine grained)		N/A	750°C/1.5h	HIP & PWHT
Mod1F			N/A	700°C/10h	HIP & over tempered HAZ
Mod1G			800°C/0.5h	700°C/1h	HIP & fine grained HAZ
Mod1H			960°C/0.5h	700°C/10h	Normalized below Ac1:820°C
Mod3	1040°C /0.5h	740°C /1h	N/A	N/A	Add 0.1%Ta, low N & Ti

The Mod3 adopted reduced nitrogen to decrease induced radioactivity, reduced titanium content to lower the volume fraction of Ti (CN) particles and improve toughness, and increased Ta to suppress grain growth during hot isotropic pressure (HIP) process. The IEA specimens were normalized at 1040°C for 40 minutes and tempered at 750°C for 60 minutes. The Mod1 series were firstly normalized at 1040°C and tempered at 750°C, followed by a second normalizing at 1100 °C for 120 minutes, an intermediate heat treatment at 960°C for 30 minutes, and finally tempered from 700 to 800°C. The details of heat treatments are summarized in Table 1. Aims of these heat treatments for Mod1E, F, G and H are equivalent to HIP, HIP+PWHT (post-welding heat treatment), HIP+over tempered HAZ (heat affected zone) and fine grained HAZ, respectively. The Mod3 specimens were normalized at 1040°C for 30 minutes and tempered at 740°C for 60 minutes. Ac1 and Ac3 are the temperatures at which austenite begins to form on heating (820°C) and at which transformation of ferrite into austenite is completed upon heating (910°C), respectively.

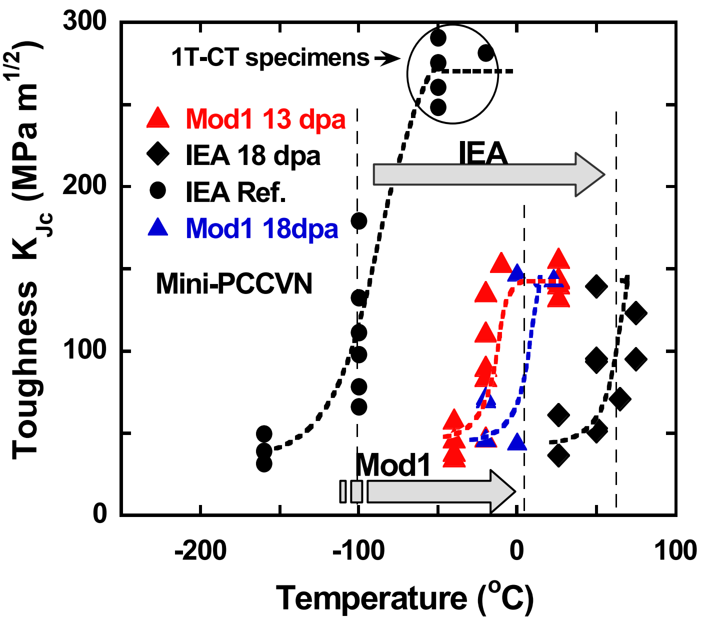

Fig. 1. Temperature dependence of fracture toughness of F82H specimens irradiated to 18 dpa   Results indicate remarkable reduction of radiation effect on fracture toughness due to optimization/tightening of tempering condition. Miniaturized bend bar specimens were used. Data shown in circle were measured from large size (1T-CT: 1 inch thickness) specimens.

(ii) Fracture toughness (DBTT-shift)

After irradiation, the DBTT is known to be dominated by hardness or flow stress level. Some of the tensile results of irradiated weld joint specimens indicated that the post-irradiation flow stress level might be reduced by modification of tempering conditions [4]. Based on this knowledge, ion and neutron irradiation experiments have been carried out to examine the dependence of post-irradiation hardness and ductility on tempering conditions using hardness and tensile specimens, respectively [5]. The specimens were tempered between 700 and 800°C for 0.5 to 10 hrs before irradiation. Results showed that longer tempering times are beneficial for reducing the post-irradiation hardness. Miniaturized bend bar specimens (half size of 1/3-CVN specimen) with fatigue pre-crack were tempered at higher temperature and/or for longer time. The specimens were irradiated to 20 dpa and tested at several temperatures. Figure 1 shows the results. Data points for IEA-F82H show the result at a reference tempering condition of 750 °C for 1h. Data for strong tempering conditions, noted as a "Mod1 Series" clearly exhibit lower DBTT after irradiation. The DBTTs are about RT and 70°C for Mod1 and IEA irradiated at 18 dpa, respectively . The DBTT reduced about 50°C. Comparing between 13 and 18 dpa for Mod1, the DBTT shift does not change so much. This suggests that the DBTT saturate at about 10 dpa. Although the 20 dpa damage level is much less than the target of 100 dpa for DEMO, the tendency for the DBTT-shift to saturate with increasing damage level suggests that the large improvement of irradiation performance of DBTT would be maintained at higher damage levels [6].

(iii) Tensile

Specimens irradiated to 20 dpa at temperatures below 400°C exhibited hardening and reduction of elongation. Figure 2 shows radiation hardening behavior for F82H IEA, Mod1 and Mod3 specimens irradiated to around 20 dpa. The addition of Ta and reduction of N and Ti in Mod3 did not cause a negative effect and the proof stress before irradiation for Mod3 was similar to that for IEA, as shown by line arrow in Fig.2. The results of irradiation hardening showed that irradiation hardening behavior of Mod3 specimen was equivalent to that of IEA specimen. The hardening saturates around 10 dpa. Before irradiation, the hardness of Mod1A, B and G group, which corresponds to IEA and Mod3, was lower than that of Mod1C, F and H group in this series. This tendency is retained even after irradiation; lower dislocation density before irradiation induces lower radiation hardening. In the case of 13 dpa, the radiation hardening of Mod1G is the lowest in these specimens. After normalizing and tempering treatments, heat treatments at 800°C for 0.5 hours and 700 °C for 1 hour adopted for Mod1A and 1G could reduce the irradiation hardening successfully. These results showed that appropriate heat treatments could reduce irradiation hardening significantly. However, addition of Ta and/or reduction of N and Ti were not so much effective for irradiation hardening.

As indicated above, the tempering condition affected the post-irradiation flow stress level. Again, application of middle tempering temperature improves ductility after irradiation. Also, the tendency toward saturation at damage levels suggests the feasibility for DEMO application.

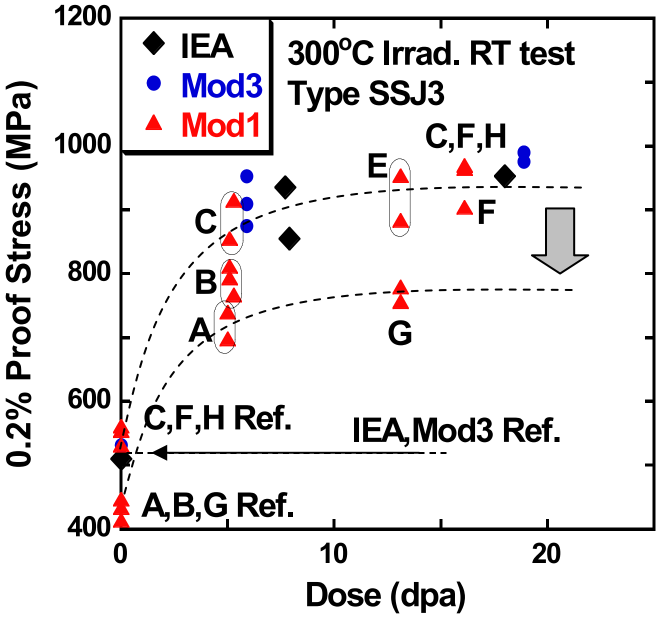

Fig. 2. Dependence of 0.2% proof stress on irradiation damage Tensile specimens were SS-J3 types and tested at room temperature. The irradiation hardening behavior is improved by heat treatmens. Reference means the proof stress before irradiation.

(iv) Creep under irradiation

Creep under irradiation has been evaluated from the diameter change of pressurized tube specimens irradiated to about 5 dpa at temperatures ranging from 300 to 500°C. Figure 3 shows hoop stress dependence of irradiation creep at 300 and

500°C for F82H IEA. Creep strain exhibited the burst at the stress level about 350 and 200MPa for those irradiated at 300 and 500°C, respectively. The burst seems to be correlated with yielding, but the verification is necessary. Comparing the microstructures for the hoop stresses between 0 and 250 MPa, the precipitates were almost same size in the case of 300 °C. In the case of 500°C, however, the precipitate size was twice larger than the case of 300 °C [7]. The number of the tests is still limited; however, creep strain seems to be almost proportional with both stress and damage levels. It should be noted that the magnitude of creep strain introduced during irradiation is rather limited (<0.01%/dpa at 300°C). Therefore, creep under irradiation is not considered to be a critical issue at 300°C.

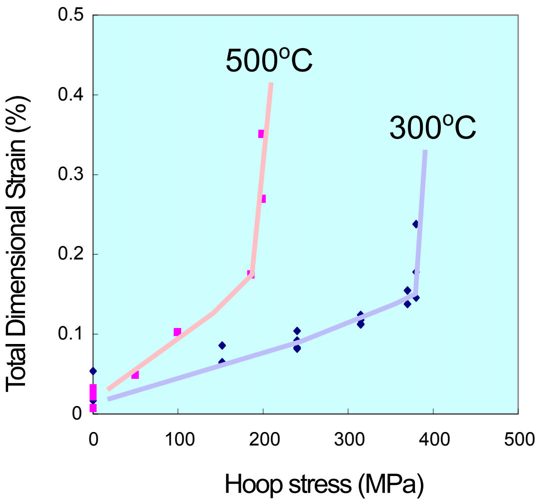

Fig. 3. Hoop stress dependence of irradiation creep at 300 and 500°C

(v) Fatigue

Fatigue loading caused large cyclic softening after irradiation to 4 dpa at 250°C, although the effect of irradiation on fatigue life (number of cycles to failure) was not strong in a constant strain amplitude test [8]. Large softening, however, may cause accumulation of fatigue damage at structural discontinuities. The fatigue mechanism changes to channel type fracture by irradiation for large number of cycles in low strain range. This issue should be considered. Cyclic softening behavior was also examined with cold worked hardened specimens to analyze cyclic softening behavior.

(vi) Impact for structural integrity

The beneficial effect of appropriate tempering condition of temperature and time seems to reduce the effects of irradiation damage on structural integrity. Cyclic softening behavior needs to be taken into account for the structural integrity of the DEMO application, because accumulation of fatigue damage at structural discontinuities is expected.

3. Summary

Results of irradiation experiments on mechanical properties at temperatures from 250 to 500°C at damage levels up to 20 dpa indicated that the irradiation effects were in a manageable range for TBM and DEMO systems. Improvements of post-irradiation toughness and ductility by optimization and tightening of tempering condition are quite beneficial to expand the service condition of RAF/M and seem to deliver more flexibility for DEMO design. The methodology of improving post-irradiation toughness and ductility is also expected to be applicable for other RAF/M steels.

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