Reduced Activation Ferritic Steel R&D in US/Japan Collaborative Research

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Abstract. Material performance of reduced activation ferritic steels (RAFS) and their response to neutron irradiation, which have been investigated by utilizing fission reactors under the US/Japan collaborative research program (JUPITER), are summarized. Rather high resistance to neutron irradiation and helium was recognized for 9Cr-2W RAFS; irradiation hardening and helium embrittlement of RAFS were evaluated to be much less than for other candidate materials. Alloy design of high-temperature steels and the development of oxide dispersion-strengthened steels have been progressing.

1. Introduction

Reduced-activation ferritic steels (RAFS) have been the prime candidate for structural materials in the DEMO reactor design and beyond [1-3], where the transmutation helium-induced embrittlement as well as neutron irradiation embrittlement are considered to be the critical issues for reactor operation [4,5]. Material performance of RAFS and their response to neutron irradiation have been investigated by utilizing fission reactors under the US/Japan collaborative research program (JUPITER). The goal of the program was focused on understanding material behavior under dynamic and complex effects of neutron irradiation, such as varying temperature irradiation effects, stress effects and transmutation effects.

Among the various candidates for fusion blanket structural materials, RAFS have shown rather high resistance to the degradation of material performance caused by neutron irradiation [1,2] and/or helium implantation [6,7]. The superiority of RAFS to other candidates in the material performance under a fusion environment is considered to be due to the martensitic structure in the RAFS, which contains a large number of trapping sites for lattice defects and helium atoms that prevent them from aggregating into defect and/or helium clusters so as to cause the degradation of the steels.

For highly efficient energy conversion, an increased operating temperature of the reactor has been advocated. Vital efforts have been made for RAFS to improve their high-temperature properties, such as creep, fatigue and creep-fatigue properties. Development of oxide dispersion strengthening (ODS) steels is a possible method toward the improved properties [8,9]. Another effort has been also made for the Japanese low-activation ferritic steel (JLF-1) by considering a new super critical water blanket system integration where high-temperature strength rather than low-temperature fracture toughness would be more important for the breeder component.

In this paper, the experimental results on RAFS obtained in the JUPITER program are summarized, and the recent progress in the material development for the improvement of high-temperature strength is reported.

2. Material Response to Neutron Irradiations

2.1 Irradiation Embrittlement

Investigation of the irradiation temperature dependence of the $\Delta\sigma_Y$-ΔDBTT relationship of RAFS for fusion application has been necessary, since the operation temperature of fusion reactors is expected in the temperature range where the materials response of RAFS to neutron irradiation significantly depends on irradiation temperature. Previous work clearly showed that FFTF/MOTA irradiation induced hardening and softening below and above 410°C, respectively, and the hardening increased with decreasing temperature, while the softening saturated above 430°C [10]. Figure 1 shows the dependence of material behavior of RAFS on irradiation temperature, and it indicates that material behavior, such as irradiation hardening, swelling and microstructure evolution, significantly depends on irradiation temperature. Understanding the mechanism of such behavior is essential for blanket design and for the further development of advanced RAFS with superior high-temperature properties. An addition of Ni enhanced irradiation hardening [11].

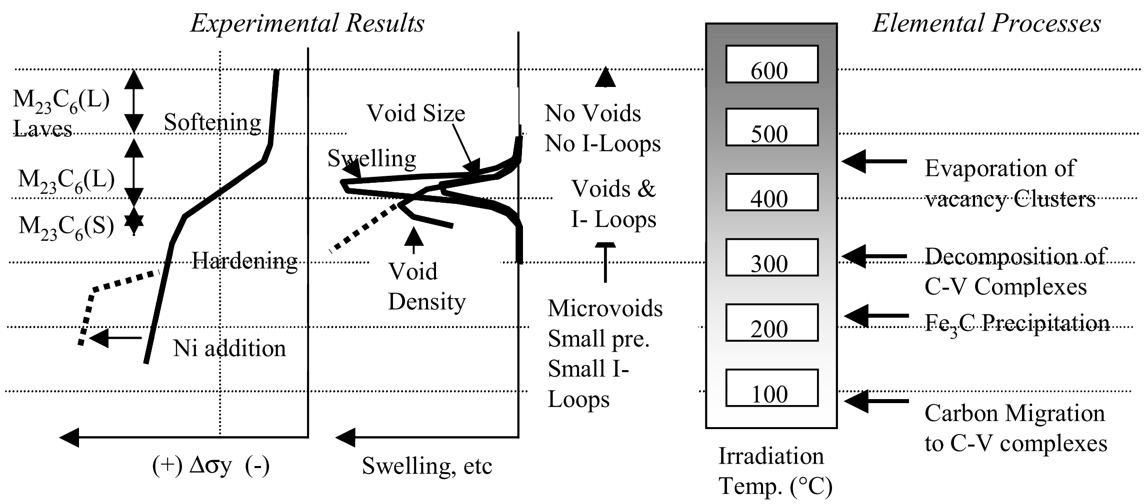

FIG.1. Material behavior-irradiation temperature diagram of RAFS

Figure 2 shows the relation between ΔDBTT and $\Delta\sigma_Y$ of RAFS following neutron irradiation together with that of 9Cr-1Mo steels for comparison [2]. Neutron dose dependence of ΔDBTT is also shown. A linear dependence between those two properties when hardening is observed is expected from work on light-water reactor pressure-vessel steels. The shift in DBTT of RAFS is rather smaller than that of the conventional 9Cr-1Mo steels (dotted line). It is worth noting that irradiation embrittlement appears to saturate above 10 dpa in RAFS. Thus, the irradiation embrittlement is not considered a critical issue for RAFS toward fusion application, although the saturation of ΔDBTT above 10 dpa should be confirmed experimentally to >100 dpa. Irradiation softening at 460°C was also accompanied by an increase in the DBTT, which could not be interpreted in terms of hardening mechanism. Since this shift in DBTT does not cause any changes in the fracture mode, the shift in DBTT is considered to be due to reduction of cleavage fracture stress, which can be interpreted in terms of precipitation of tantalum-rich particles [1,12]. For the improvement of fracture toughness after high temperature irradiation, the irradiation-induced softening should be suppressed through the stabilization of microstructure, which might cause an increase in high-temperature strength, such as creep and fatigue strength. Details will be shown in a later section.

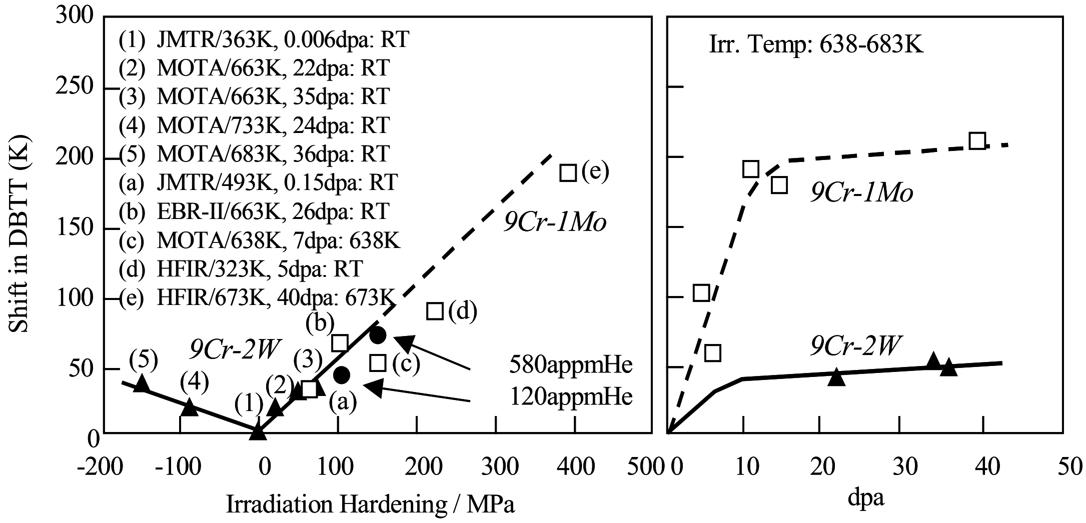

FIG.2. Effects of irradiation temperature on the shift in DBTT in ferritic steels.

2.2 Effects of Transmutation Helium

It is well known that in austenitic stainless steels, which will be utilized for ITER, several tens atomic ppm of helium causes severe embrittlement at elevated temperature. Embrittlement is accompanied by a change in fracture mode from cleavage to intergranular cracking caused by bubble formation at grain boundaries. Although the RAFS has a superior resistance to irradiation-induced embrittlement and void swelling under fission neutron irradiation with low helium concentration, helium-induced embrittlement can be expected to be a critical issue of the RAFS in a fusion environment where much more helium is produced.

Assessment of helium embrittlement of RAFS was done by one of the authors who investigated the effect of helium implantation on ductile-brittle transition temperature by means of small punch (SP) test technique (Fig.3) and concluded that an implantation with helium up to 580 at.ppm at a temperature below 432K resulted in no enhancement of the shift in the SP-DBTT [13]. The relation between ΔDBTT and $\Delta\sigma_Y$ after the He implantation is also shown in Fig 2, indicating that the data fell on the line that was obtained for RAFS irradiated with neutrons without any significant helium generation. High resistance to the helium embrittlement of RAFS is due to high trapping capacity of their martensitic structure for helium atoms. It is, however, supposed that helium implantation at rather high temperatures could cause a degradation of fracture toughness because of the evolution of helium bubbles during implantation.

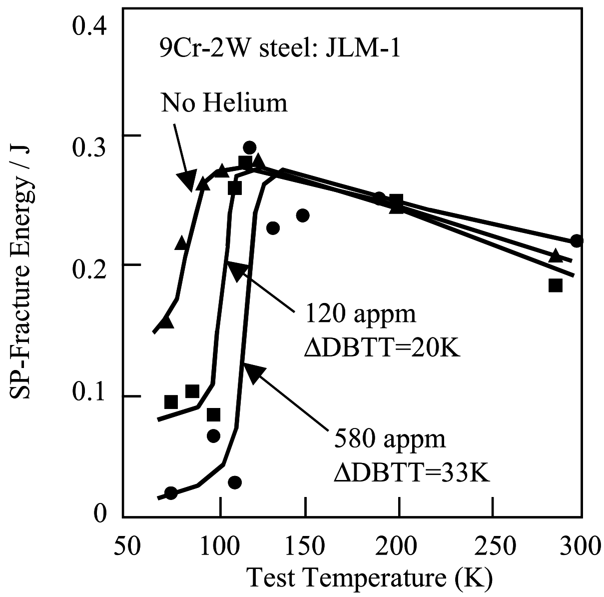

FIG.3. Effects of helium implantation on the ductile-brittle transition behavior of RAFS.

2.3. Varying Temperature Irradiation

In the fusion environment, the irradiation temperature is expected to vary during the reactor operation. Figure 4 shows the irradiation history of the HFIR-13J capsule for varying temperature irradiations. To make sure of the effects of one unit of the irradiation cycle, a similar varying temperature irradiation was carried out in JMTR. Varying temperature irradiation effects on tensile properties and positron annihilation lifetime, were investigated in two types of stepwise increasing varying temperature irradiation, from 220°C to 420°C and from 340°C to 420°C [14]. Based on the results, rate theory was used to model the microstructural evolution in RAMS in order to clarify the role of .the defect clusters in the irradiation hardening. The simulation study was done successfully for the stepwise varying temperature irradiation as shown in Fig.5.

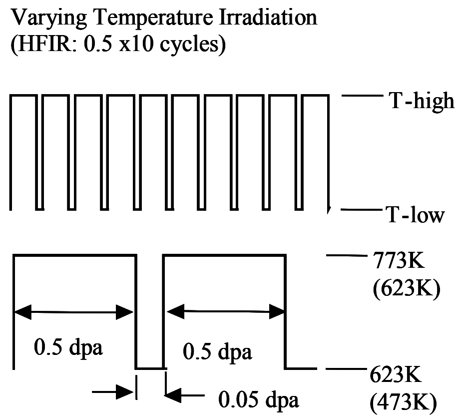

FIG.4. Irradiation history of the HFIR-13J.

Although austenitic steels and vanadium alloys suffered very complicated effects during varying temperature irradiation, which was shown by a completely different microstructure evolution in comparison to the constant temperature irradiation, the RAFS were rather resistant to the varying temperature irradiation: no significant change in the material behavior was observed.

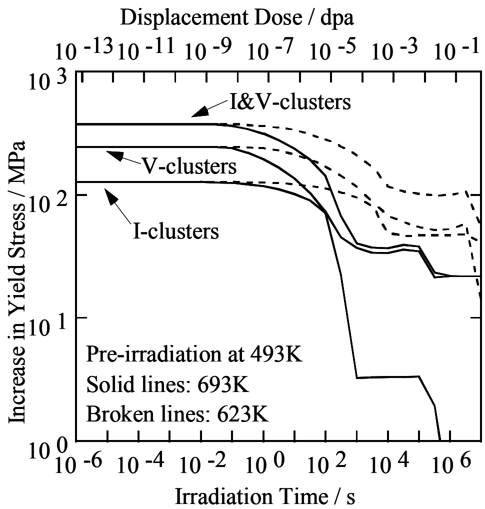

FIG.5. Results of computer simulation of irradiation behavior of RAFS under the varying temperature irradiation.

Thus, the mechanism of the irradiation hardening and/or embrittlement of RAFS have been understood through the US/Japan collaborative research, which a new alloy design for improvement of material performance under neutron irradiation can be done by taking account of the material response to irradiation.

3. Improvement of High-Temperature Properties

3.1. Development of high-tungsten steels and ODS steels

In a commercial fusion reactor, elevation of the blanket system operating temperature is required for highly efficient energy conversion. Consequently, alloy design of high-temperature steels and the development of oxide dispersion strengthened (ODS) steels have been critical issues for RAFS. Relation between applied stress and rupture time of newly developed steels are shown in Fig. 6. The JLS steels are high-W RAFS whose tungsten concentration was increased to improve high-temperature strength by means of solid-solution hardening [8]. Since the reduction of fracture toughness caused by Laves phase is of concern

for high-W steels, fracture toughness measurements after thermal aging are in progress.
The PNC-FMS steels are the ODS steels developed by Japan Nuclear Cycle Development Institute [9], showing a significant improvement of high-temperature creep strength, as also shown in Fig.6. Study of ODS steels irradiated to high dpa has been planed.

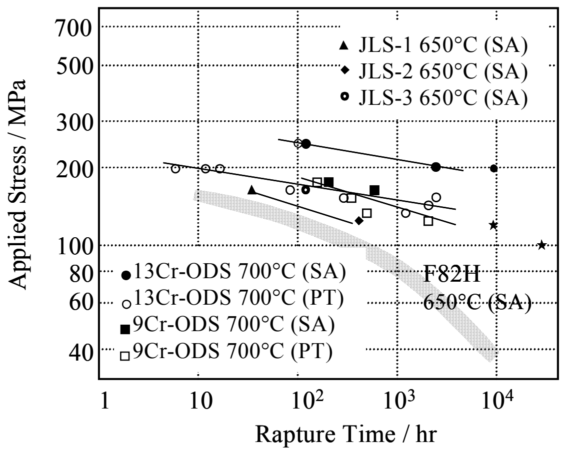

FIG.6.Improvement of the high temperature creep properties of RAF and ODS steels.

The US/Japan collaboration has been effective in accumulating an irradiation database and in understanding the mechanism of irradiation effects of RAFS. The irradiation data obtained up to now indicate the feasibility of using ferritic steel for applications to fusion technology, because of their high resistance to degradation of material performance by displacement damage and helium. It is considered that the good material performance under neutron irradiation is due to the martensitic structure in the steels, which contain a large number of sinks for radiation-induced defects. A continuous effort to accumulate a sufficient design database, however, should be made in order to qualify and finally validate the application of the steel to commercial reactors.

Development of high-temperature RAFS and ODS steels has been progressing successfully. A material-blanket system integration study is also necessary for the qualification of material performance of RAFS as a structural material for fusion reactor.

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