Irradiation Effects on Reduced Activation Ferritic/Martensitic Steels -Mechanical Properties and Modeling-

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Abstract. Recent results of irradiation experiment on reduced activation ferritic/martensitic steels are introduced. Macroscopic models of post irradiation tensile and fatigue properties obtained from the results are shown. Concept of the models should be essential for future design criteria development. A simulation method on irradiation hardening is also introduced

1. Introduction

Service temperature of reduced activation ferritic/martinsitic steels (RAF/Ms) for the DEMO is expected to range from around 300 to 550 ^{o}C [1]. 14MeV D-T fusion neutrons produce displacement damages and transmuted gas atoms (e.g. He atoms) in the ma-terials to high levels. Displacement damage level during service period is expected to attain 100 to 150 dpa (displacement per atom) or even higher, depending on the opera-tion temperature, while He generation rate of about 10 appmHe/dpa[1]. This causes to change both microstructure and mechanical properties of the material to considerable degrees.

Major issues introduced by irradiation are reductions of elongation, fracture toughness and fatigue life in addition to the dimensional change during irradiation (e.g. irradiation creep and swelling) [2-6]. These changes often limit service condition and the lifetime of the components. Improvement of the design methodology and the irradiation response of the steels based on the understanding of the mechanisms of the irradiation effects are the useful methods for these issues. Irradiation effects on tensile property, fracture toughness and fatigue property are introduced in the following with results recently obtained.

Results of the modeling activities are also introduced. The models for the macroscopic behavior (macroscopic models) are expected to become the key elements of the future design methodology [7]. These macroscopic models are of the empirical models for e.g. plasticity and fatigue [8]. The models for microstructural change and micromechanics (microscopic models) are expected to deliver both the basics of macroscopic models and the methodology to reinforce irradiation materials database. Because of the limited capability of the irradiation facilities, the latter is expected to become one of the key methods to solve this issue. Mechanisms of the microstructural change and the relation between hardening and the microstructure are the major subjects of the microscopic models.

2. Irradiation effects

2.1 Tensile properties

At temperatures below 400^{o}C, irradiation often causes hardening and reduction of elongation, as shown in Fig. 1 and 2 [2]. One of the issues for the structural integrity is the reduction of the margin to ductile fracture. Improvement of the design methodology is one of the methods for this issue [7]. This idea is based on the fact that even if the tensile elongation decreased to a considerable degree, residual ductility to fracture evaluated by reduction of area is still large enough [8]. This is introduced in “4. 1 Macroscopic models” in more detail. Figure 2 shows damage level dependence of yield stress σ_y and total elongation ε_t of the tensile tests on one of the Japanese RAF/Ms F82H. The change tends to saturate with damage level of 10 dpa.

Therefore the methods applicable at 10 dpa level are expected to be available at higher damage levels.

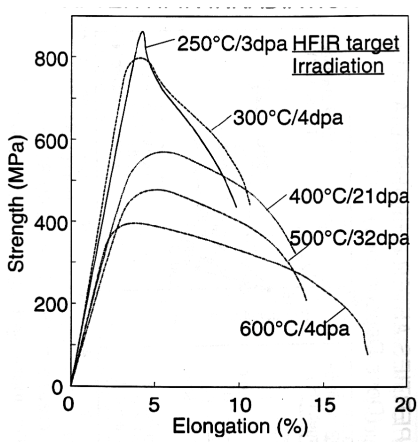

Fig. 1 Typical engineering stress-strain curves after irradiation

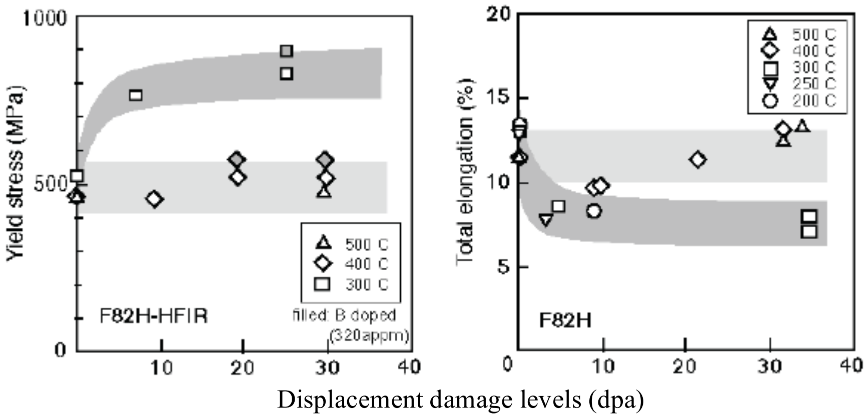

Fig. 2 Damage level dependence of Yield stress and Total elongation

2.2 Fracture toughness

Decrease of fracture toughness and upper shelf energy, as well as increase of DBTT are occurred by irradiation also below 400 ^{o}C [1, 2]. Figure 3 shows the damage level dependence of DBTT of F82H. DBTT tends to saturate with damage levels.

DBTT shift has been indicated to have close relationship to irradiation hardening [1]. As seen in Fig. 4, DBTT-shift seems to be accompanied by irradiation hardening, although the scatter for DBTT is large because of its nature of the brittle fracture. These facts suggest that the reduction of the flow stress/hardness (after irradiation) may result in smaller toughness degradation. The arrows in the figure indicates “He effects”, which is discussed in “3.2 He effect on fracture” in more detail.

2.3 Fatigue properties

It has been often indicated that residual ductility is closely related to the number of cycles to failure (Manson-Coffin relation: M-C relation) for steels without irradiation [9]. Residual ductility after irradiation is typically about half of that before irradiation, as indicated in “4.1 Macroscopic models”. This suggests no large degradation is expected by irradiation (typically, ¼ of that before irradiation is expected from the M-C relation). Considering into the large scatter of fatigue life, the deviation is rather small, as seen in Fig. 5. Indeed, irradiation effect on the number of cycles to failure does not seem to be large [10]. However, relatively large degradation was seen at a small strain range of about 0.5% in plastic strain.

Fatigue life was reduced by around one order. This reduction was accompanied by the change of the fracture surface: the feature indicates that fatigue crack was propagated with channel fracture like mechanism, suggesting an important role of dislocation channeling at small strain ranges [10]. Channel deformation to fracture is occurred by a characteristic dislocation microstructure in deformed metals and alloys after irradiation [11].
Irradiation effect on fatigue life does not seem to be large, except the reduction at small strain ranges. On the other hand, a large softening during fatigue loading of irradiated specimen is a fact need to be taken into account for the development of design methodology (this will be discussed further in “4.1 Macroscopic models”).

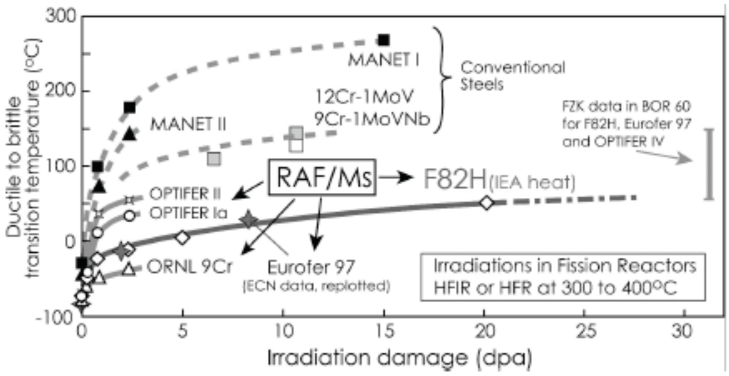

Fig. 3 Damage level dependence of DBTT for RAF/Ms and conventional steels

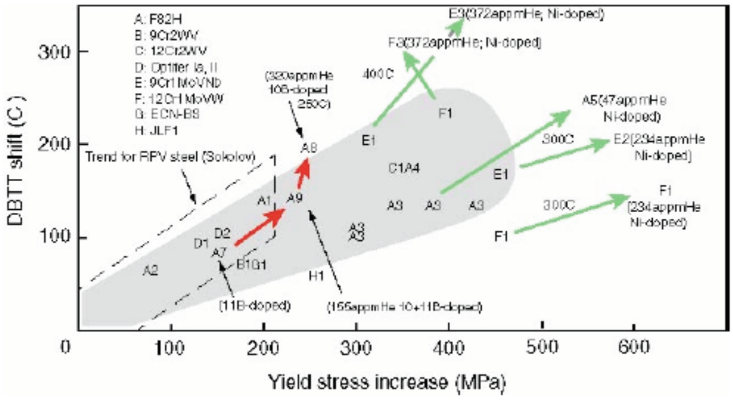

Fig. 4 Relation between DBTT-shift and increase of yield stress by irradiation

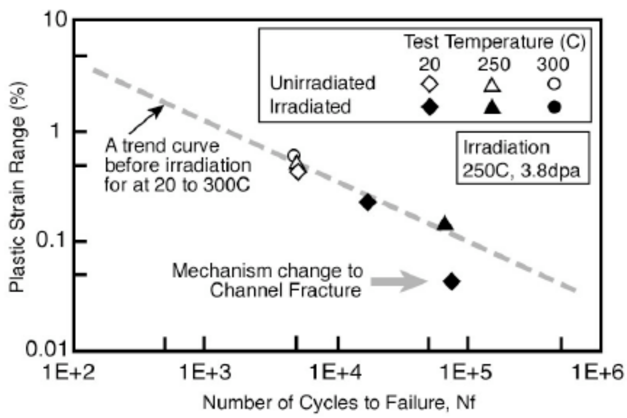

Fig. 5 Fatigue life (Number of cycles to failure and plastic strain range) before and after irradiation

3. Feasibility to blanket structural materials

3.1 Reduction of tensile elongation and DBTT-shift

Significance of the reduction of elongation and DBTT-shift after irradiation is discussed. Elongation falls rather rapidly with damage levels up to 5 and 10 dpa, depending on temperature (see, Fig. 2). Above this damage level, the change with dose becomes smaller. This suggests that the design criteria applicable to 5-10 dpa level is expected to be also available at higher dpa levels. Although the large reduction of et is occurred, residual ductility to fracture evaluated from the reduction of area RA was not small [8]. Therefore, most of RAF/Ms including F82H should be applicable to DEMO, as far as the residual ductility to fracture is concerned. This is one of the keys for the development of design criteria, as indicated in "4.1 Macroscopic modeling" [7, 8].
Mechanical loading by coolant pressure becomes zero for the water-cooled blanket. Water pressure at 200 ^{o}C is relatively small; 25% of that at 300 ^{o}C. Upper limit for DBTT is thought to be between 100 ^{o}C to 300 ^{o}C depending on operation and inspection methodologies (300^{o}C is the lower bound of water temperature during normal operation). Suppose the upper temperature limit is 150 ^{o}C for the coolant condition without significant mechanical loading, the results for RAF/M of F82H, Eurofer and ORNL9Cr seem to be applicable up to a damage level of about 30 dpa and even higher.
As described above, two significant issues of irradiation induced changes of reduction of elongation and DBTT-shift can be reduced or solved by the development of design methodology and optimization of operation scenario. It should be noted that these optimistic view relying on the saturation tendency with damage levels. He effect may violate this trend to some extent, as introduced in the next section.

3.2 He effect on fracture

Specimens doped with 10B and 58Ni to produce He atoms in the materials has been irradiated with fission neutrons. Effect of the doping was indicated by arrows in Fig. 4. Red arrows correspond to 10B doping, while green arrows for 58Ni doping. As seen in the figure, DBTT-shift seemed to be accompanied by hardening depending on the specimens tested. 10B doped specimens exhibited rather larger DBTT-shift to the hardening, however. It might suggest a small He effect to enhance fracture other than hardening. Although this rather small effect is seen, DBTT-shift seemed to be domi-nated by hardening at He levels of below 400 appm, and the plots almost follows a re-lation of ΔDBTT=0.5$\Delta\sigma_y$. It is well recognized that Ni-doping enhances irradiation hard-ening. Effect of B on irradiation hardening has not been clearly understood, however the result suggests some effect to enhance irradiation hardening [12]. So, it might be concluded that doping of B and Ni was accompanied by hardening resulted in DBTT-shift, but the He effect on DBTT-shift or hardness has not clearly identified at He levels below 400 appm. To distinguish the He effect from those by B and Ni addition, isotopic tailoring experiments with 10B, 11B, etc. have been also carried out.
With increasing He levels, irradiation hardening seems to be enhanced with He. Figure 6 shows He level dependence of irradiation hardening obtained by dual ion-beam irradiation (simultaneous irradiation with both Fe+3 and He+). Results clearly indicates that additional hardening had occurred at He levels >1000 appm with He implantation rates of 10appmHe/dpa and 100 appmHe/dpa [13]. This additional hardening would have significant meaning, because it may reduce residual ductility to fracture. Indeed, tensile results reported by Henry after irradiation in SINQ PSI clearly indicates the additional hardening at He levels >1000 appm reduced residual ductility [14]. Additional hardening by He seems to reduce residual ductility to limit the lifetime of the component. Also, the method to reduce the loss of residual ductility is quite important for the application of RAF/M to blanket structural materials.

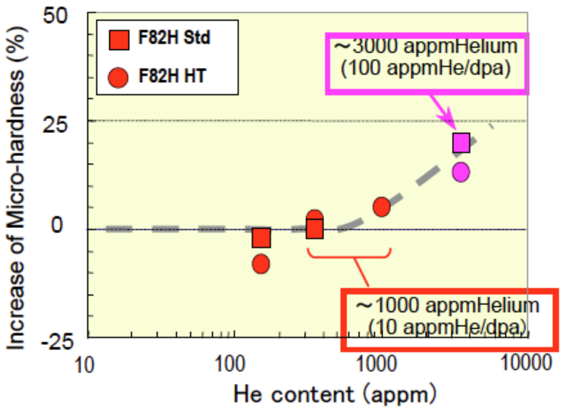

Fig. 6 Additional hardening by He occurred by dual-ion (Fe and He ions) beam irradiation

4. Modeling

4.1 Macroscopic models

Some of the macroscopic models are obtained from empirical relationships. Because those macroscopic models are applied to predict deformation and fracture of the component, the models need to be formulated taking the deformation mode into account to provide good insight to the mechanical response of the component [7].

(a) Tensile properties

"Tensile test results" are the load-displacement relations of particular "structures" with typical configurations of round bar and strip. Therefore the relations exhibit clearly the effect of configurations in the strain region of plastic instability. Irradiation hardened specimen readily exhibits plastic instability. To escape from such "configuration effect", therefore, In Situ measurement of deformation of the specimen has been carried out (see figure 7). True stress-true strain (Ts-s) relation obtained by this test technique is shown in Fig. 8. Ts-s relations before and after irradiation indicated that the relation is well described with an equation of $\sigma_y=A(\varepsilon_0+\varepsilon_p)^n$ without regard to the degree of irradiation hardening [7, 8]. One of the important out put from Ts-s relation is that even engineering stress-strain relations exhibit only work softening, Ts-s relations indicate residual work hardening capability. Also, residual ductility to fracture remains about half of that before irradiation for RAF/Ms. Therefore, the margin to the onset of ductile fracture under bending and torsion condition should be considerably large. In addition, fracture condition (true stress and equivalent true strain of $\varepsilon_0+\varepsilon_p$) under uniaxial tension is almost unchanged before and after irradiation. This also suggests the residual ductility after irradiation may be obtained readily from flow stress level and the equation. This seems to be valuable to obtain allowable stress level, therefore, this is one of the keys for design criteria development.

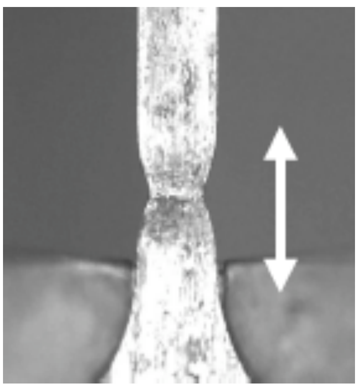

Fig. 7 Strain distribution in irradiated F82H tensile specimen

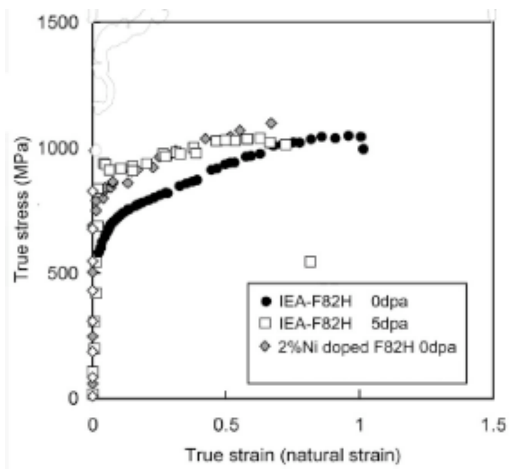

Fig. 8 (a) True stress-strain curves of F82H before and after irradiation

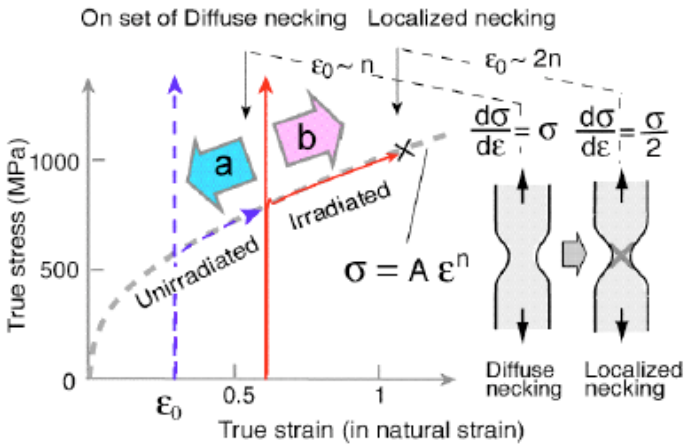

Fig. 8 (b) Relation of True stress-strain curves and ductile fracture condition before and after irradiation

(b) Fatigue behavior

Effect of irradiation on the fatigue life does not seem to be strong, except that accompanied by the mechanism change to channel fracture at low strain ranges [10]. On the other hand, cyclic stress amplitude decreased with fatigue loading. The stress amplitude decreased to approach to that of without irradiation. This large decrease also causes accumulation of fatigue damage where the cyclic softening occurred relatively rapidly (by e.g. stress concentration) resulting in shorter fatigue life of the structure.

The fatigue mechanism change to channel fracture by irradiation at a small strain range is also an issue to be examined in future.

4.2 Microscopic modeling to expand the capability of irradiation materials database

For the designing and the licensing of the components without irradiation effect, a number of materials data are required. On the other hand, irradiation effects are de-pending on temperature, damage level and external stress on the component. There-fore, it may be expected that larger number of materials data over various conditions would be required. However, capability of the irradiation facilities is apparently limited even if IFMIF is in operation. Extending of the capabilities of irradiation materials data-base by modeling and numerical simulation would be one of the methods to compen-sate the limited capability of irradiation facility. Feasibility of this methodology is an issue in future, but it may contain a method to predict microstructural development at atomis-tic level of mechanisms. Also, the relation between microstructure and some of the mechanical properties such as hardening is one of the key methods to be developed.

5. Improvement of irradiation performance

As indicated previously, additional hardening is occurred with He levels of >1000appm in addition to enhance the separation at boundaries in RAF/Ms at temperatures below 400 ^{o}C. This may limit the lifetime of the component. To increase the margin to ductile fracture and reduction of DBTT, reduction of flow stress level after irradiation seem to be beneficial. Longer tempering time (an example of stronger tempering condition) resulted in lower hardness before and after irradiation. For the issue of DBTT-shift by irradiation, reduction of non-metallic inclusions should be also effective.

6. Summary

(1) Accomplishment by the activities of RAF/M development is briefly introduced.
(2) Effect by reduction of elongation and DBTT-shift will remain in the range capable of management by the improvement of design methodology, except the He effect at levels of >1000 appm.
(3) Irradiation effects on fatigue behavior is rather small, except for the mechanism change at a small strain ranges. However, the large cyclic softening of irradiation hardened steel may become an issue.
(4) Transmutation produced He atoms at concentrations >1000 appm causes additional hardening and enhance the separation at crystallographic boundaries. These may limit the lifetime of the component with RAF/Ms.
(5) For the improvement of the design methodology, empirical models of the irradiation effects on several mechanical properties have been conducted. A constitutive equation for plasticity has been proposed.
(6) Optimization of the tempering condition to reduce hardness after irradiation is one of the methods to expand the margin to fracture after irradiation.

Reference

[1] S. Jitsukawa, A. Kimura, A. Kohyama, R. L. Klueh, A. A. Tavassoli, B. van der Schaaf, G. R. Odette, J. W. Rensman, M. Victoria and C. Petersen, “Recent results of the reduced activation ferritic/martensitic steel development”, J. Nucl. Mater. 329-333 (2004) 39-46.

[2] S. Jitsukawa, M. Tamura, B. van der Schaaf, R. L. Klueh, A. Alamo, C. Petersen, M. Schirra, P. Spaetig, G. R. Odette, A. A. Tavassoli, K. Shiba, A. Kohyama and A. Kimura, “Development of an extensive database of mechanical and physical properties for re-duced-activation martensitic steel F82H”, J. Nucl. Mater. 307-311 (2002) 179-186.

[3] Akihiko Kimura, Ryuta Kasada, Akira Kohyama, Hiroyasu Tanigawa, Takanori Hirose, Kiyoyuki Shiba, Shiro Jitsukawa, Satoshi Ohtsuka, Shigeharu Ukai, M.A. Sokolov, R.L. Klueh, Takuya Yamamoto and G.R. Odette, “Recent progress in US–Japan collabora-tive research on ferritic steels R&D”, J. Nucl. Mater. 367-370 (2007) 60-67.

[4] R. L. Klueh, “ELEVATED-TEMPERATURE FERRITIC AND MARTENSITIC STEELS AND THEIR APPLICATION TO FUTURE NUCLEAR REACTORS”, ORNL/TM-2004/176, Nov., 2004.

[5] A. Kohyama, M. Seki, K. Abe, T. Muroga, H. Matsui, S. Jitsukawa and S. Matsuda, “Interactions between fusion materials R&D and other technologies”, J. Nucl. Mater. 283-287 (2000) 20-27.

[6] B. van der Schaaf, D. S. Gelles, S. Jitsukawa, A. Kimura, R. L. Klueh, A. Möslang and G. R. Odette, "Progress and critical issues of reduced activation ferritic/martensitic steel development", J. Nucl. Mater. 283-287 (2000) 52-59.
[7] K. Suzuki, et. al., "Review of intense irradiation data and proposal of design concept for structural integrity", J. Nucl. Mater., (in press).
[8] T. Taguchi, S. Jitsukawa, M. Sato, S. Matsukawa, E. Wakai and K. Shiba, "Post irradiation plastic properties of F82H derived from the instrumented tensile tests", J. Nucl. Mater. 355 (2004) 457-461.
[9] for example, L. F. Coffin, "A study of the effect of cyclic thermal stresses on ductile metals", Trans. ASME, 76, 1954, p 931.
[10] Yukio Miwa, Shiro Jitsukawa and Minoru Yonekawa, "Fatigue properties of F82H irradiated at 523 K to 3.8 dpa", J. Nucl. Mater. 329-333 (2004) 1098-1102.
[11] for example, F. A. Garner, "Irradiation Performance of Cladding and Structural Steels in Liquid Metal Reactors" in 6 of "Materials Science and Technology (vol. 10)", R. W. Cahn, P. Haasen and E. J. Kramer, Eds., 1994, p. 520, VCH Publishes, Weinheim.
[12] E. Wakai, S. Jitsukawa, H. Tomita, K. Furuya, M. Sato, K. Oka, T. Tanaka, F. Takada, T. Yamamoto, Y. Kato, Y. Tayama, K. Shiba and S. Ohnuki, "Radiation hardening and embrittlement due to He production in F82H steel irradiated at 250 °C in JMTR", J. Nucl. Mater. 343 (2005) 285-296.
[13] M. Ando, et. al., to be published in J. Nucl. Mater.
[14] J. Henry, X. Averty, Y. Dai and J.P. Pizzanelli, "Tensile behaviour of 9Cr–1Mo tempered martensitic steels irradiated up to 20 dpa in a spallation environment", J. Nucl. Mater. 377 (2008) 80-93.