On the Potentiality of Using Ferritic/Martensitic Steels as Structural Materials for Fusion Reactors

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Abstract. Reduced activation ferritic/martensitic (RAFM) steels are the reference as structural materials for the future fusion reactors. They have proven to be a good alternative to austenitic steels for their higher swelling resistance. However, RAFM steels exhibit irradiation-induced low temperature hardening and increase in the ductile-to-brittle transition temperature, which imposes a severe restriction on their reactor applications at temperatures below 300°C. Furthermore, a high density of small helium bubbles has been recently evidenced in specimens proton-irradiated at about 300°C to a dose of 10 dpa, which could affect their fracture mechanical behavior at intermediate temperatures. Their temperature window of use is presently limited by a drop in mechanical strength at about 600°C. So, new variants that can better resist at high temperatures, are currently being developed, mainly using a stable oxide dispersion. The potentiality of using present RAFM steels and the variants being developed for the first wall of future fusion reactors are reviewed below.

1. Introduction

In fusion reactors, the first wall and breeding-blanket components will be exposed to plasma particles and electromagnetic radiation and will suffer from irradiation by 14 MeV neutrons. The high energy neutrons will produce displacement damage (via displacement cascades) and impurities (i.e. H and/or He atoms) via transmutation nuclear reactions within structural materials. Key parameters for the first wall in fusion power reactors (fusion power: 3-4 GW, operational mode: quasi-continuous) are the following [1]: total neutron flux: 10-15x10^{14} n/cm^2.s; neutron wall loading: 2-3 MW/m^2; integrated wall load: 10-15 MWy/m^2 (100-150 dpa in steels); surface heat load: 0.1-1 MW/m^2; volume power density: 20-30 W/cm^3; maximum irradiation temperature: ≥ 650°C; gas production rates: 10-15 appm He/dpa, 40-50 appm H/dpa (in steels).

2. Structural Materials for First Wall and Breeding-Blanket Applications

Candidate structural materials for first wall and breeding-blanket applications have a chemical composition that is based on low activation elements (Fe, Cr, V, Ti, W, Ta). They include mainly reduced activation ferritic/martensitic (RAFM) steels, vanadium alloys and SiC/SiC ceramic composites. Among them, the RAFM steels are presently considered as the most promising structural materials, as they have achieved the greatest technical maturity, i.e. qualified fabrication routes, welding technology and a general industrial experience are already available. The RAFM steels that are currently under extensive investigation include two large casts of F82H and EUROFER 97 and laboratory casts of the series of OPTIMAX alloys. The F82H steel was developed in Japan. It is investigated as part of the IEA (International Energy Agency) Fusion Materials Internationally Coordinated Program on ferritic/martensitic steels. The F82H steel contains 7.65 wt.% Cr, 2 wt.% W, Mn, Mo, V, Ta, Si and C below 1 wt.% in sum total, and Fe for the balance. The EUROFER 97 steel was developed in Europe within the EFDA (European Fusion Development Agreement) Program. Its chemical composition is the following: 8.93 wt.% Cr, 1.07 wt.% W, Mn, Mo, V, Ta, Si and Cr below 1 wt.% in sum total, and Fe for the balance. The RAFM steels known as OPTIMAX steels were developed by the Fusion Technology Materials (FTM) group of the Centre of Research in Plasma Physics (Association EURATOM-Swiss Confederation) [2]. They contain about 9 wt.%Cr and their detailed composition results from optimisation of previous 12 wt.% Cr steels, as MANET for instance, where Ni, Mo and Nb have been replaced by the W, V and Ta low activation elements.

3. Advantages and Drawbacks of RAFM Steels

3.1. Advantages

In addition to their favorable cost, availability and engineering data base, the RAFM steels present a lower activation than stainless steels and a better surface heat capability (4.32 KW/K.m at ambient temperature for F82H, i.e. three times that of stainless steels) due to their lower coefficient of linear thermal expansion and higher coefficient of thermal conductivity [3]. At temperatures above 300°C, the RAFM steels are expected to exhibit a good resistance to swelling (1 vol.% per 100 dpa as compared to 1 vol.% per 10 dpa in stainless steels).

3.2. Drawbacks

The RAFM steels exhibit a drop in tensile strength at about 600°C [4], a strong reduction in creep strength at temperatures above 600°C and a significant stress softening in low cycle fatigue tests. In addition, the RAFM steels have a bcc structure and, like other materials of this type, they exhibit a ductile-to-brittle transition temperature (DBTT). In the unirradiated state, the DBTT of RAFM steels lies well below room temperature, that is between -80 and -90°C for the F82H, OPTIMAX A and EUROFER 97 alloys.

3.3. Effects of Irradiation

Irradiation at temperatures below 300-350°C leads to strong hardening and loss of ductility (see Figure 1, [5]), i.e. to embrittlement. Transmission electron microscopy (TEM) observations showed that the strong radiation hardening evidenced for RAFM steels at irradiation temperatures below about 300-350°C seems to correlate with the irradiation-induced dislocation loop microstructure (size and density evolution as a function of dose) rather than with the helium amounts produced (see Figure 2, [6]). The DBTT also increases drastically, as for instance up to -5°C for OPTIMAX A neutron-irradiated at 250°C to 2.5 dpa (see Figure 3, [5]) and up to +53°C for F82H neutron-irradiated at 300°C to 2.5 dpa. Neutron irradiation at temperatures below 300°C to 100-150 dpa is expected to yield a DBTT well above room temperature. At higher irradiation temperatures, the DBTT is not expected to increase significantly [3]. The effects of high He/dpa ratio still need to be investigated. A high density of small helium bubbles (about 1nm) has been recently evidenced using TEM (see Figure 4) in specimens of the F82H steel that were irradiated in SINQ (the Swiss Spallation Neutron Source, neutron-proton mixed spectrum, gas production rates: 50 appm He/dpa and 450 appm H/dpa in steels) at about 300°C to a dose of 10 dpa [6]. The impact of such a distribution of helium bubbles on the fracture properties of the F82H steel is under investigation. Preliminary mechanical test results seem to indicate that the helium amounts produced correlate well with the fracture behaviour of RAFM steels, i.e. a larger amount of helium yields a stronger rate of increase in the DBTT, at least at irradiation temperatures below about 300°C.

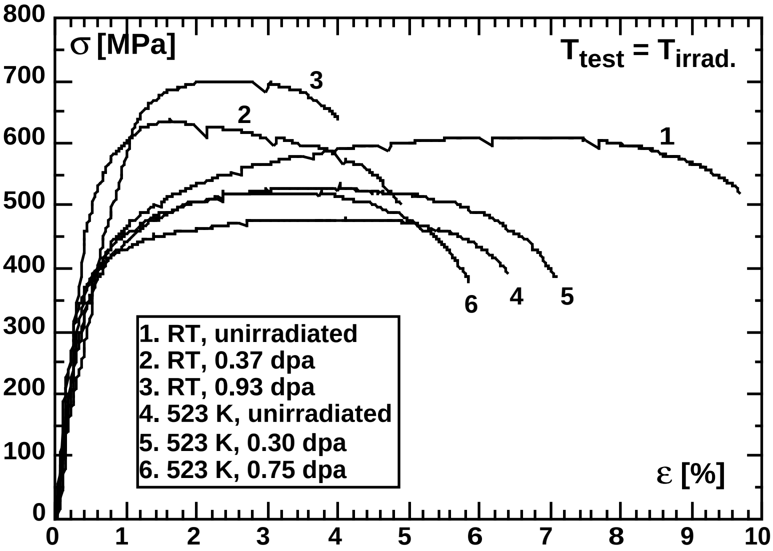

FIG. 1. Tensile stress-strain curves of unirradiated and proton-irradiated OPTIMAX A, after [5].

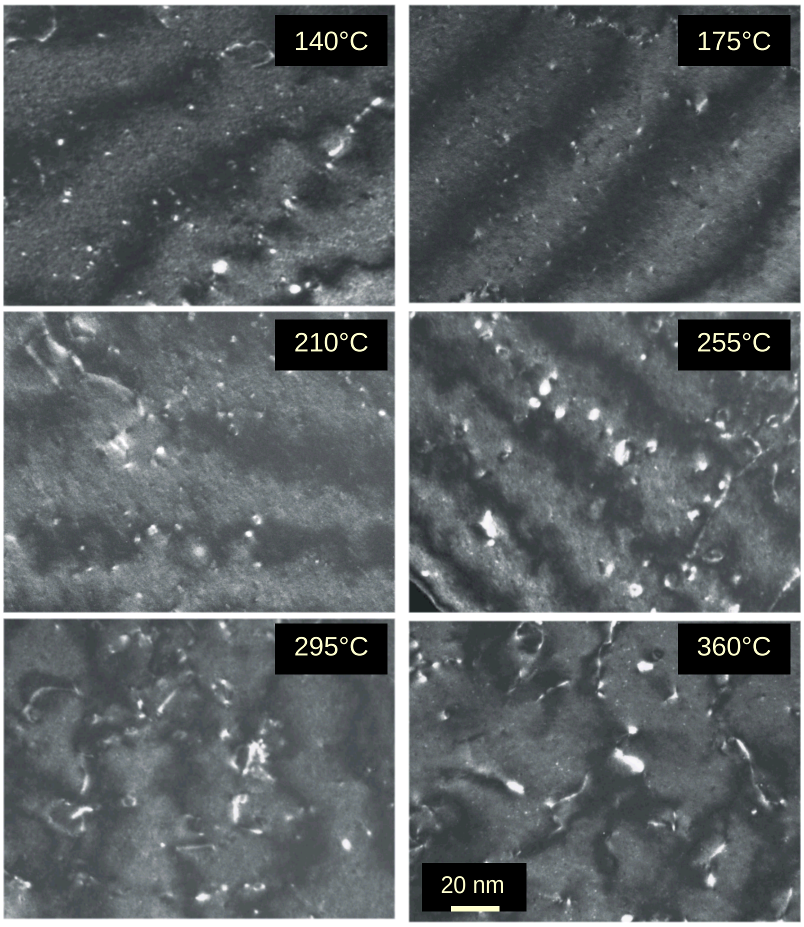

FIG. 2. Irradiation-induced dislocation loops of interstitial type in F82H irradiated in SINQ at various temperatures to about 10 dpa, after [6].

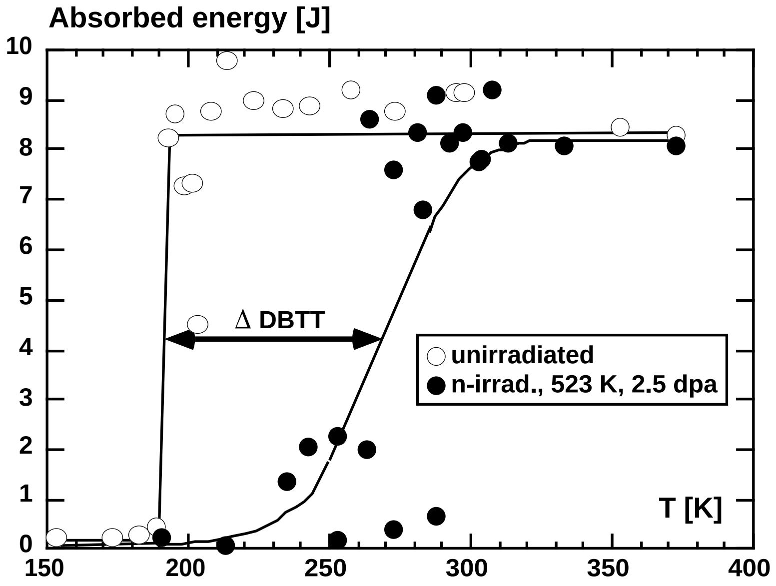

FIG. 3. Charpy impact energy versus temperature for OPTIMAX A, before and after neutron-irradiation at 250°C to 2.5 dpa, after [5].

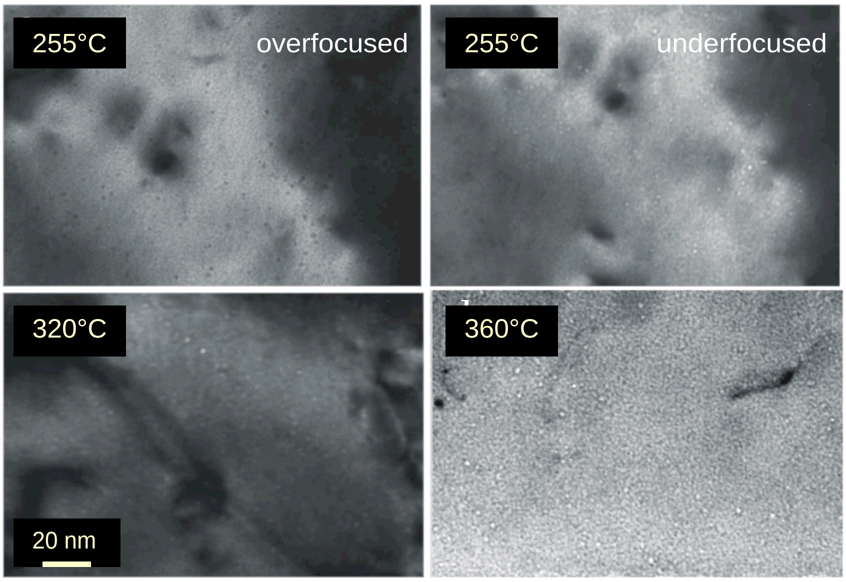

FIG. 4. Irradiation-induced helium bubbles in F82H irradiated in SINQ at various temperatures to about 10 dpa, after [6].

3.4. Summary

In summary, the temperature window of use of RAFM steels is presently approximately 350-550°C, the lower value being limited by irradiation-induced embrittlement effects and the upper limit by a strong reduction in mechanical strength. To decrease the lower temperature limit involves decreasing the DBTT before irradiation. If one may expect to lower the DBTT value by acting upon the composition and/or the impurity level, it seems unrealistic to obtain a DBTT below room temperature after neutron irradiation at temperatures below 300°C to doses of about 100-150 dpa. One way to get round this problem would consist in maintaining the temperature above 350°C and/or to anneal regularly the fusion reactor at high temperature to recover the DBTT obtained in unirradiated conditions. On the other hand, it is expected that adding a fine dispersion of strong particles to the RAFM steels could contribute to increase the upper temperature limit. ODS (Oxide Dispersion Strengthened) steels with the EUROFER 97 as matrix material and Y_2O_3 particles as reinforcement material are currently under development in Europe in the frame of the EFDA Program. Preliminary mechanical test results [7] showed a significant shift of the mechanical strength to higher temperatures, but unfortunately they also revealed a strong increase in the unirradiated DBTT value, with respect to the EUROFER 97. Obviously, fabrication routes still need further improvement.

4. Conclusion

This paper shows the need to promote a strong dialog between reactor designers and material science experts to define a reactor concept which takes into account the constraints imposed by potential materials as well as engineering and economical considerations. While the use of existing irradiation facility such as SINQ can provide useful data on materials, the availability of an intense source of 14 MeV neutrons, such as IFMIF (International Fusion Materials Irradiation Facility), is a requisite for the final qualification of the selected materials.

5. References

[1] EHRLICH, K., ‘The Development of Structural Materials for Fusion Reactors’, Phil. Trans. R. Soc. Lond. A **357** (1999) 595.
[2] VICTORIA, M., et al., ‚The Microstructural Stability and Mechanical Properties of Two Low Activation Martensitic Steels’, (Proc. 17th ASTM Symp. on Effects of Radiation on Materials), (GELLES, D.S., Ed.), ASTM, Philadelphia (1995) 721.
[3] TAVASSOLI, F., ‘Presents Limits and Improvements of Structural Materials for Fusion Reactors’, J. Nucl. Mater, to appear (2002).
[4] SPÄTIG, P., BALUC, N., ‘Proton Irradiation up to 1 dpa of Plate, for He Effect Testing’, (Report on EFDA Task TW1-TTMS-001 deliverable 3), (2001).
[5] BALUC, N., et al., ‘The Mechanical Properties and Microstructure of the OPTIMAX Series of Low Activation Ferritic-Martensitic Steels’, J. Nucl. Mater. **283-287** (2000) 731.
[6] JIA, X., et al., ‘The Impact of Irradiation Temperature on the Microstructure of F82H Martensitic/Ferritic Steel Irradiated in a Proton and Neutron Mixed Spectrum’, J. Nucl. Mater. 305 (2002) 1.
[7] SCHÄUBLIN, R., et al., ‘Microstructure and Mechanical Properties of Two ODS Ferritic/Martensitic Steels’, (Proc. 10th International Conference on Fusion Reactor Materials), to appear in J. Nucl. Mater. (2002).