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ScienceDirect
Journal of Nuclear Materials 367–370 (2007) 33–41
journal of nuclear materials
www.elsevier.com/locate/jnucmat

Status of reduced activation ferritic/martensitic steel development

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Abstract

Recent research results obtained in Europe, Japan, China and the USA on reduced activation ferritic/martensitic (RAFM) steels are reviewed. The present status of different RAFM steel products (plate, powder HIPped steel, many types of fusion and diffusion welds, unirradiated and irradiated states) is sufficient to present a strong case for the use of the steels in ITER test blanket modules. For application in DEMO, more research is needed, including the use of the International Fusion Materials Irradiation Facility (IFMIF) in order to quantify the effects of large amounts of transmutation products, such as helium and hydrogen.

1. Introduction

Reduced activation ferritic/martensitic (RAFM) steels are the reference structural materials for future fusion power reactors, as they have achieved the greatest technology maturity, i.e. qualified fabrication routes, welding technology and general industrial experience is already available. However, the temperature window for use of RAFM steels is presently about 350–550 °C, the lower value being limited by irradiation-induced embrittlement effects and the upper value by a strong reduction in mechanical strength.

Recent advances in the fields of fabrication, mechanical properties, manufacturing of blankets, effects of irradiation, compatibility experiments, development of coatings, databases and design rules, and development of new steel variants are successively addressed below. They refer mainly to four

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doi:10.1016/j.jnucmat.2007.03.036

kinds of RAFM steels: the F82H (7.46 wt% Cr, 1.96 wt% W, 0.21 wt% Mn, 0.15 wt% V, 0.10 wt% Si, 0.09 wt% C, 0.023 wt% Ta, 0.006 N, Fe for the balance) that was developed by the Japan Atomic Energy Research Institute (now Japan Atomic Energy Agency) and the JFE Corporation and was investigated as part of the IEA (International Energy Agency) Implementing Agreement on Fusion Materials, the JLF-1 (9.0 wt% Cr, 2.0 wt% W, 0.45 wt% Mn, 0.25 wt% V, 0.2 wt% Si, 0.1 wt% C, 0.07 wt% Ta, 0.05 wt% N, balance Fe) that was developed by Japanese universities, the EUROFER 97 (8.9 wt% Cr, 1.1 wt% W, 0.47 wt% Mn, 0.2 wt% V, 0.14 wt% Ta, 0.11 wt% C, balance Fe) that was developed in Europe within the framework of the EFDA (European Fusion Development Agreement) programme, and the Chinese Low Activation Martensitic steel (CLAM) with the following chemical composition: 8.98 wt% Cr, 1.55 wt% W, 0.40 wt% Mn, 0.21 wt% V, 0.15 wt% Ta, 0.11 wt% C, balance Fe.

2. Recent advances

2.1. Fabrication

A new heat of 300 kg of JLF1-1 was recently produced [1]. Also, a new batch of about 8 tons of EUROFER 97, referred to as the EUROFER 97-2, with different product forms (forgings, plates and tubes) was manufactured. Preliminary mechanical testing confirmed the high reproducibility of the steel properties in the reference condition [2]. Fig. 1 shows the limited differences between various heats of RAFM steels. In the near future, tests on the EUROFER 97-2 after irradiation will be conducted to check the reproducibility of the properties after irradiation.

A heat similar to EUROFER 97 using Fe-54 instead of natural iron is now being produced [3]. Then, miniaturized Charpy and tensile specimens with cores made of Fe-54 substituted EUROFER 97 steel will be fabricated. Such specimens shall be irradiated with neutrons in the High Flux Isotope Reactor (HFIR) in Oak Ridge (USA) so that about 2.3 appm He/dpa will be produced from Fe-54 inside the core of the specimens via (n, alpha) reactions. Note that about 10 appm He/dpa shall be produced in fusion relevant irradiation conditions. Nevertheless, it is expected that Fe-54 EUROFER 97 steel should provide information on the effect of helium on mechanical properties.

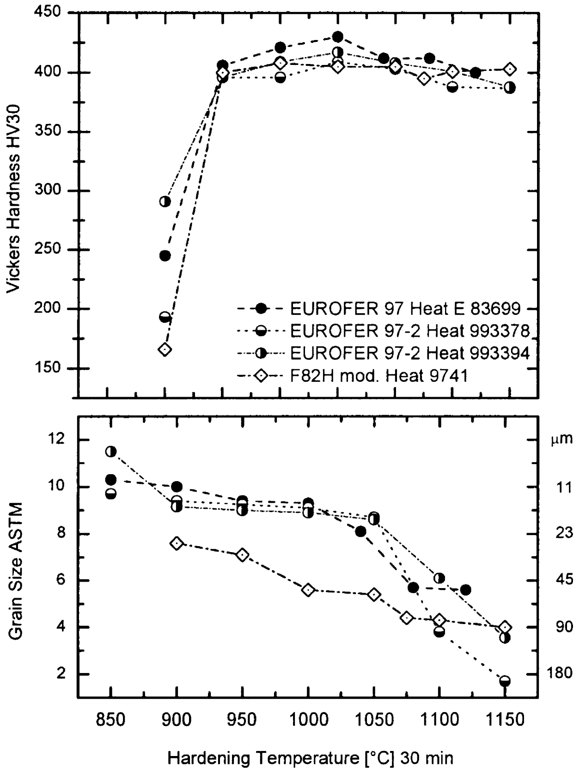

Fig. 1. Vickers hardness and grain size versus normalizing temperature for various EUROFER heats [2].

2.2. Mechanical properties

The microstructure, tensile, fracture and creep properties of the CLAM steel have been characterized and compared to those of the EUROFER 97 [4]. At room temperature, a yield strength of 486.8 ± 18.6 MPa, an ultimate tensile strength of 629 ± 21.4 MPa, a uniform elongation of $8.4 \pm 0.6\%$ and a total elongation of $25.1 \pm 0.3\%$ have been measured. The CLAM appears slightly softer and more ductile than the EUROFER 97. The CLAM exhibits a ductile-to-brittle transition temperature (DBTT) of about −91 °C, similar to that of EUROFER 97, and it shows reduced creep rate and creep life with respect to the EUROFER 97.

A Master Curve analysis (according to the standard ASTM E1921) of the available F82H fracture database was performed [5]. In practice, 219 data points were assembled after constraint loss corrections and statistical effect adjustment. These data points refer to bend bar and compact tension specimens. For the EUROFER 97, a recent analysis of the available fracture database suggested that a modification of the Master Curve shape may be needed [6]. A number of results recently obtained for the EUROFER 97 are reported in [7].

2.3. Blanket issues

RAFM steels are the reference materials in Europe for manufacturing the blanket for DEMO. The Test Blanket Modules (TBMs) that Europe wants to test in ITER will therefore be manufactured from RAFM steel. The TBM can be thought of as a box $1 \times 1 \times 1\ m^3$ with many positions to be filled with sub-breeding units in the form of ‘pancakes’ or ‘boxes’. The structure has to be strong enough to withstand a helium pressure of 8 MPa. This means that the shape is complex and has to be constructed for example by laser welding or shaping with Hot Isostatic Pressing (HIPping) diffusion welding [8]. However, the EUROFER 97 was found to be sensitive to hot cracking under continuous wave YAG (yttrium aluminium garnet) laser welding [9]. Obviously, weldability studies for the TBM configurations are needed to develop suitable welding parameters and/or welding processes for defect-free welds.

In contrast to austenitic stainless steels, untreated welded joints of ferritic/martensitic steels suffer from hardening and embrittlement due to martensite formation in the weld metal and heat affected zone. To improve joint performance, Post Welding Heat Treatments (PWHTs) have to be applied. In the European program, many types of welds and HIPped products to be qualified for use in test blanket structures have been tested. Recently the PWHT of fusion welds has been investigated. Tungsten-Inert-Gas (TIG) with EUROFER 97 filler wire, Electron Beam (EB), and Laser welding have been applied to EUROFER 97 plates in the as-received condition [10]. The major result is that for EB and Laser welds, one PWHT is sufficient (annealing at 700 °C for 2 h). In the case of TIG welding, two PWHTs are preferred, as the welds are far too brittle: full austenization in order to recover a microstructure composed of uniformly distributed fine grains plus tempering to reduce hardness is needed. For complicated structures, as many as five PWHTs may be needed. These details can only be verified after final design of the TBM with mock-up tests.

The square tube production needed for several design options of the TBM has been successfully demonstrated for conventional 9Cr steels [11]. Square tube fabrication from RAFM steels should therefore be possible.

All welds must be inspected before entering service in ITER. Several analyses showed that, even for the narrowest welds required in some parts of the TBM, inspection is possible [12]. Ultrasonic inspection will allow detection of gas pore diameters above 0.2 mm and minimum defect sizes of about $0.5 \times 0.5\ mm^2$. The final design will determine which method to select, but the present work showed the potential for sound manufacturing processes in line with materials science and engineering results.

Key achievements concerning the development in JAEA of a water-cooled solid breeder ITER TBM are as follows [13]: (1) A suitable two-step post-HIPping heat treatment for the fabrication of TBMs made of F82H was developed, which allows recovery of a fine-grained microstructure from the coarse-grained microstructure resulting from the HIPping process: homogenizing at 1150 °C followed by normalizing at 930 °C. (2) A direct bonding method of tungsten armor onto the F82H has been developed by using a solid state bonding method based on uniaxial hot compression without any artificial compliant layer. (3) It was found that the thermal fatigue lifetime of the F82H can be predicted by using the Manson–Coffin law based on 3 D elasto-plastic stress analysis.

2.4. Effects of irradiation

2.4.1. Irradiation experiments

Following neutron irradiation at 300 °C to doses in the range 0.3–2 dpa in the BR2 reactor in Mol (Belgium), the EUROFER 97 shows strong embrittlement effects, including hardening and loss of ductility, increase in the DBTT and loss of fracture toughness [14]. However, in the dose range investigated, the radiation-induced DBTT remains well below RT. RAFM steels containing 8–9 wt% Cr and 1–2 wt% W (ORNL-9Cr2WVTa, F82H, EUROFER 97) clearly exhibit the smallest increase in DBTT for doses below 2.5 dpa (Fig. 2). The shifts in the reference temperature T_0, as determined for high Cr steels within the framework of the ‘Master Curve’ approach (standard ASTM E1921-02), appear significantly larger than the shifts in DBTT (Fig. 3). It was suggested that this fact should be accounted for in reactor design and/or safety assessments.

A number of high dose irradiations have been recently completed. Most of the corresponding post-irradiation evaluations (PIEs) are still in progress.

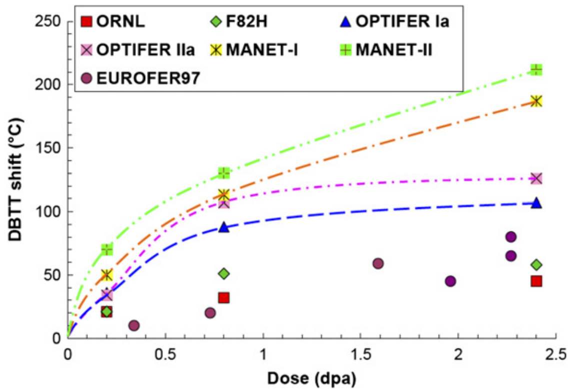

Fig. 2. DBTT shift versus dose for various RAFM steels (all neutron irradiated at 300 °C) [14].

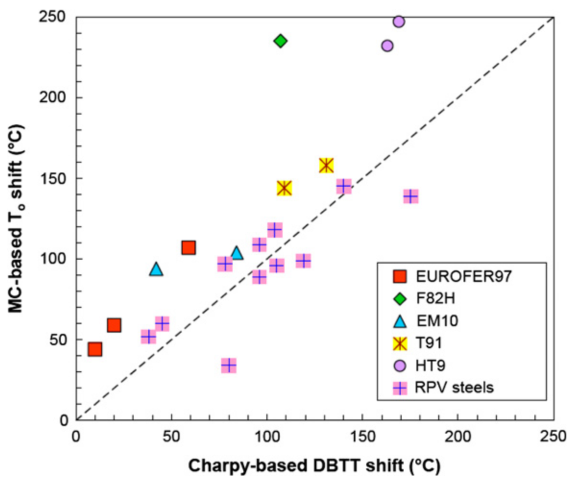

Fig. 3. Shift in reference temperature T_0 (Master Curve approach) versus DBTT shift (Charpy impact tests) for high Cr steels and RPV steels [14].

Tensile, Charpy and fatigue specimens of RAFM steels, including the EUROFER 97 in various states (various heat treatments, HIPped powder steel, and various boron contents), have been irradiated in the High Flux Reactor (HFR) in Petten (The Netherlands) at five different temperatures between 250 and 450 °C to a dose of about 15 dpa [15]. PIE is in progress.

Recent results of PIE performed on specimens of RAFM steels irradiated either in the HFR at 60 and 300 °C to 10 dpa or in the BR2 reactor at 300 °C to various doses ranging between 0.3 and 2 dpa are summarized in [16,14,17], respectively. They show that the low temperature tensile hardening saturates at about 1.5 dpa, while no saturation for 300 °C is observed at 9 dpa (Fig. 4). The tensile hardening at 60 °C irradiation is 1.5 order of magnitude more rapid than that at 300 °C. The tensile hardening ($\Delta\sigma_y$) of 300 °C irradiated EUROFER 97 follows a linear trend with the square root of the dose (ϕ) up to about 2 dpa, in accordance with $\Delta\sigma_{y,\mathrm{RT}} = 240(\phi^{1/2})$. The general trend line up to 9 dpa is described well by $\Delta\sigma_{y,\mathrm{RT}} = 616[1 - \exp(\phi/6.7)]^{1/2}$. Note that following irradiation at temperatures above 400 °C, very small tensile hardening usually occurs [18]. Following irradiation at 300 °C, the EUROFER 97 shows an increase in DBTT that is strongly dependent on the fabricated product [16]. In the present case, the smallest increase in DBTT has been measured for 8 mm plate material and 100 mm round bar in comparison with 25 mm plate material. Irradiation at 60 °C or 300 °C to 2.5 dpa reduces the ductile initiation fracture toughness of 9Cr materials by 30%, or 60%, respectively. The relationship between the tensile hardening ($\Delta\sigma_y$) and the shift in fracture toughness transition temperature (ΔFTTT) was estimated to be $\Delta\mathrm{FTTT} = 0.37(\Delta\sigma_{y,\mathrm{RT}})$ for the EUROFER 97 and $\Delta\mathrm{FTTT} = 0.53(\Delta\sigma_{y,\mathrm{RT}})$ for the F82H. The KLST impact DBTT and the FTTT were found to show almost the same transition temperatures for very similar irradiation conditions, deviating most in the unirradiated case [16]. Low cycle fatigue (LCF) for 300 °C irradiated EUROFER 97 shows a small but significant decrease (or increase) of LCF life at high (or low) strain ranges, respectively. Note that following irradiation at 250 °C to 3.8 dpa in the JMTR (Japan), the F82H did not show any change in fatigue life for most of the investigated strain ranges [18]. Good impact properties, approaching those of plate material, have been obtained for TIG and EB welds after low temperature irradiation. After 300 °C irradiation, EB welds, powder HIPped and especially TIG welds show fracture toughness of 50 down to 25% that of the original plate material. This may be improved by a better (longer and/or higher) PWHT. While martensitic materials that were not (sufficiently) tempered exhibit large irradiation-induced shifts in transition temperature, the wide transitions are caused by inhomogeneities in the weld.

Following irradiation at 300 and 500 °C to 5 dpa, and at 250 °C to 1.5 dpa, in the JMTR, TIG and HIPped joint specimens of F82H exhibit properties comparable to those of the base metal [18]. Note that HIPing was performed at 1040 °C for 5 h under 150 MPa.

Following irradiation at 325 °C to a dose in the range 32.5–42.3 dpa in the BOR-60 reactor (the

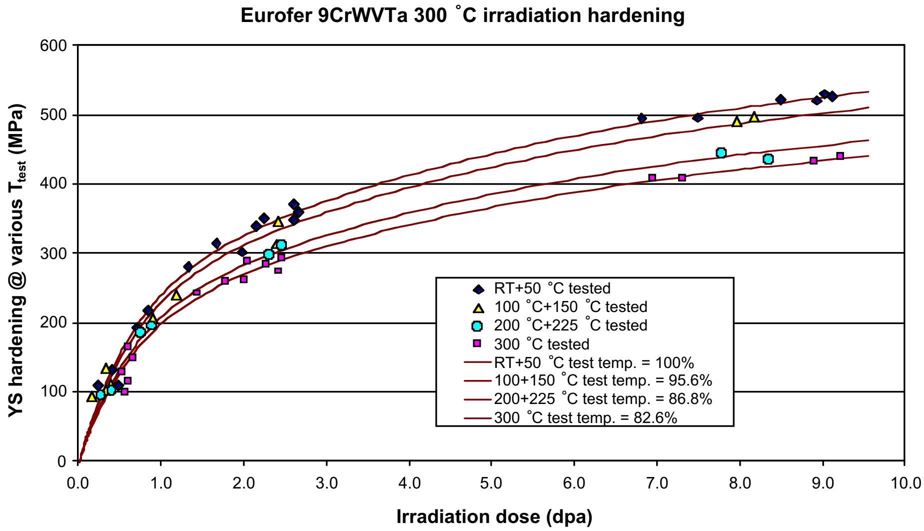

Fig. 4. Radiation hardening versus dose for the EUROFER 97 irradiated at 300 °C in the HFR and BR2 reactors and tested at various temperatures [16,17]. Note: the RT curve was taken as the reference, and the curves for the other testing temperatures have been constructed by applying a multiplication factor as indicated in the figure.

ALTAIR experiment), the EUROFER 97 showed the lowest hardening and the largest ductility as compared to conventional 9Cr1Mo ferritic/martensitic steels [19]. The hardening rate seems to decrease with increasing dose (but saturation remains to be confirmed at high doses). The loss of ductility shows no tendency to saturation [20]. Note that in the case of water-cooled blanket applications, it is desirable that the DBTT does not exceed 100 °C following irradiation to high doses [18].

Charpy, tensile and fatigue specimens of the EUROFER 97 steel have been irradiated in the BOR-60 reactor in Dimitrovgrad (Russia) to a dose of about 30 dpa [21]. This irradiation experiment is referred to as ARBOR 1. PIE is in progress. Preliminary results indicate that following irradiation at 300–330° to about 30 dpa, the DBTT is well above RT [22]. The increase in DBTT shows a tendency to saturation with increasing dose, but eventual full and complete saturation at high doses remains to be confirmed [22]. The ARBOR 2 experiment refers to a second irradiation performed in the BOR-60 reactor to about 30–40 dpa on fresh specimens of the EUROFER 97 from FZK and the CEA and on specimens pre-irradiated either in the ARBOR 1 experiment to 30 dpa or in the ALTAIR experiment to 40 dpa [21]. This second irradiation was completed in spring 2005. PIE will be performed in 2007.

An additional tensile hardening was measured for the F82H irradiated to 1.5 dpa in the JMTR when performing cyclic temperature changes between 250 and 350 °C during the irradiation, contrary to what was observed for the SA-316F austenitic stainless steel [18].

Specimens of EUROFER 97 have been irradiated with a mixed spectrum of high-energy neutrons and spallation neutrons in the Swiss Spallation Neutron Source (SINQ) at various temperatures ranging between 300 and 600 °C to various doses between 10 and 20 dpa. PIE will be performed in 2007–2008. One of the main advantages of SINQ irradiations is the generation of high rates of production of transmutation products (e.g. about 50 appm He/dpa and 450 appm H/dpa in steels).

2.4.2. Fundamental studies

Damage at a crack tip is being investigated based on transmission electron microscopy of cross section specimens prepared from F82H pre-cracked compact tension specimens that were loaded to approximately 50% of J_{IC}. Studies include an unirradiated specimen tested at −196 °C and a specimen irradiated at 400 °C to 10 dpa in the HFR and tested at room temperature [23].

By combining an independent physically motivated model of hardening as a function of dose and temperature with the estimated ratio of the shift in fracture toughness reference temperature (ΔT_0) to the radiation hardening ($\Delta\sigma_y$), it was possible to predict the behaviour of ΔT_0 and $\Delta\sigma_y$ versus dose for the F82H steel [24]. It was found that the predictions compare well with the experimental data, at least for irradiation temperatures from 250 to 385 °C.

2.5. Compatibility experiments

2.5.1. Effects of hydrogen and helium

The permeability of deuterium in the EUROFER 97 is slightly reduced by pre-irradiation (to 0.01 dpa), more strongly reduced by helium implantation (500 appm He at RT), and even more after annealing to induce helium clustering into bubbles [25]. The diffusivity is also slightly reduced by pre-irradiation and more strongly reduced by helium implantation, but this effect is partially recovered by annealing. The solubility, as derived from the ratio of permeability and diffusivity, shows a minor dependence on pre-irradiation. It is enhanced by helium implantation, but this effect is strongly reduced by annealing.

The EUROFER 97 has a rather high susceptibility for H embrittlement, with threshold concentrations for transition from ductile to completely brittle behaviour ranging from about 1 wppm at room temperature to a few wppm at about 200 °C [26]. The density of traps for hydrogen in the EUROFER 97 is about one order of magnitude higher than in the F82H, yielding reduced hydrogen permeability. The main trapping sites are probably the interfaces between martensite laths, carbide precipitates and dislocations.

The F82H and 9Cr3WVTaB steels have been implanted with helium at 550 °C or 600 °C using an implantation rate between 1.1 and 1.7×10^{-3} appm He/s. Accumulated helium concentrations ranged between 100 and 1000 appm, the latter value being comparable to helium accumulation at the end of blanket unit lifetime [27]. No significant degradation of the creep resistance at 550–600 °C was observed with respect to non-implanted materials. However, it was observed that helium concentrations above about 600 appm have significant effect on the ratio of DBTT shift to the radiation hardening, accompanied by a transition to intergranular fracture [24]. It was suggested that the large shifts measured might be limiting conditions for application of RAFM steels at low temperatures (below about 400 °C).

2.5.2. Resistance to water corrosion

Slow Strain Rate Tests (SSRTs) were performed on unirradiated specimens of EUROFER 97 and specimens irradiated with neutrons to 1.25 dpa, at 100 and 300 °C in a high-pressure water circulation loop, in three different environments: air, oxygenated water and hydrogenated water [28]. No major stress corrosion cracking was observed, even in irradiated specimens. It was concluded that water-cooled components of EUROFER 97 could be safely operated, given proper coolant chemistry control and low-to-moderate dose irradiation. Similar results have been obtained for the F82H irradiated at 250 °C to 2 dpa in the JMTR [18].

Following neutron irradiation to 1 dpa, HIPped variants of the EUROFER 97 exhibit a corrosion fatigue crack growth rate eight to ten times higher than that of the base EUROFER 97 [29].

2.5.3. Resistance to Pb–17Li corrosion

Corrosion analysis following exposure of specimens of EUROFER 97 to flowing Pb–17Li (about 0.3 m/s) in the PICOLO loop at 480 °C for times up to 12000 h showed that the corrosion behaviour of the EUROFER 97 is similar to that of the MANET and F82H-mod steels; typical steel elements are dissolved and for short test times the samples exhibit smooth surfaces [30]. The corrosion attack of the EUROFER 97 was observed to be of uniform type with a corrosion rate of about 90 μm per year (Fig. 5). This corrosion rate is slightly smaller than for the other RAFM steels investigated but with equal activation energy.

2.6. Development of coatings

With the aim of protecting RAFM steels against first wall conditions, millimetre-thick tungsten coat-

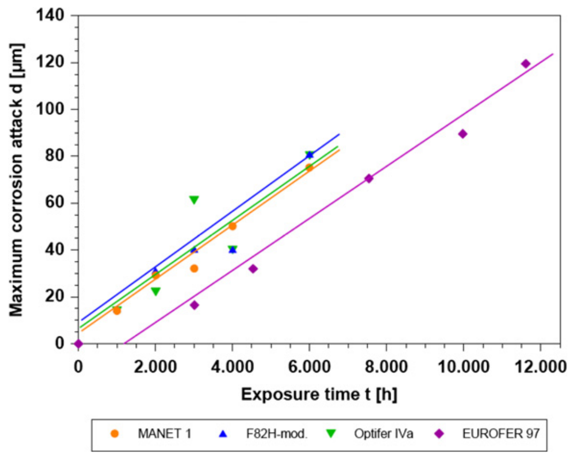

Fig. 5. Corrosion rates of various FM steels in liquid Pb–17Li [30].

ings have been deposited on EUROFER 97 substrates by chemical vapour deposition (CVD) on one side and by plasma spraying on the other. The quality of the W-CVD coatings was found to be excellent, especially in terms of high density and excellent adhesion to the steel substrates [31]. The only drawback relates to the necessary presence of a thin interlayer (e.g. copper) between the steel substrate and the tungsten-CVD coating, as the adherence of such coatings to steel substrates is close to zero. Plasma sprayed coatings showed a very good resistance to thermal shock.

Insulator Al-based coatings about 20 μm-thick have been developed for the CLAM steel using CVD of Al, followed by oxidization to induce the formation of a 1 μm-thick alumina coating at the external surface of the coatings [4]. The electrical resistivity at the surface of the specimens was measured to be about 10^3–10^4 $\Omega\,m^2$.

2.7. Databases and design rules

The design and safety analyses must assure the safe and reliable operation of the blankets, and require sound design rules and stable fabrication and inspection methods.

Experimentally determined materials behaviour data form the basis of the design rules and criteria. At present these data are collected within the IEA framework. A large dataset on F82H steel, the first IEA heat of RAFM steel produced on an industrial scale in Japan, forms the core of these data. More data are rapidly becoming available for EUROFER 97, the RAFM steel fabricated in Europe, in both the reference condition and following irradiation to 30 dpa.

The development of design rules also depends strongly on experimental results on RAFM steels. Recently, much effort has been devoted to the lifetime prediction of steels subjected to fatigue. Thermal and isothermal data are available. If hold-times are not too long, the rules are well supported by experimental evidence. Cyclic softening of RAFM steels might be a serious problem as far as thermomechanical loading is concerned as deformation localization can lead to local instabilities and then to failure rather than to creep and/or fatigue [32].

The incorporation of fracture toughness in the rules has not yet been done. The different domains of plastic and totally brittle fracture cannot easily be included. Fracture mechanics criteria to define design rules for solid/solid and solid/powder HIPped joints of EUROFER 97 are being developed [33].

Preliminary lifetime assessment of TBM subcomponents and modules by finite element calculations have shown that conditions similar to the ITER operating conditions lead to an accumulation of plastic deformation in a critical region of the first wall under cyclic thermal and mechanical loads [34]. Further simulations considering extreme heat fluxes and pressures shall be carried out to check the range of admissible loads and to verify existing design rules. Further data of cyclic tests are needed to extend the available material parameters.

The database on the F82H, EUROFER 97 and the conventional 9Cr–1Mo steels has been updated [35]. This work is part of an international collaboration within the framework of the IEA fusion materials implementing agreement collaboration on ferritic/martensitic steels.

2.8. Towards new steel variants

The upper temperature for use of RAFM steels is presently limited by a drop in mechanical strength at about 500–550 °C. New variants that can withstand higher temperatures are currently being developed, mainly using stable oxide dispersion. These include the EUROFER 97 reinforced with 0.3 wt% Y_2O_3 particles, as well as reduced activation ferritic steels, mainly based on the Fe(12–14)CrWTi composition, also reinforced with about 0.3 wt% Y_2O_3 particles [36].

An issue with such Y_2O_3dispersion strengthened alloys is joining technology because particles aggregate and float in the molten state. An alternate welding process, Friction Stir Welding (FSW), is being studied with experiments completed on MA957 and ODS EUROFER [37,38]. Preliminary results showed that significant softening can take place in MA957 and significant Y_2O_3 coarsening can occur in ODS EUROFER during the FSW process.

When exposed to humid air at 750 °C, the ODS RAFM steels exhibit a resistance to oxidation which is much better than that of the martensitic steels and similar to that of the 316SS austenitic stainless steel [18]. This good oxidation resistance was attributed to formation of a homogeneous film at the surface as a result of the suppression of oxygen diffusion due to the presence of Y_2O_3 particles.

Although the ODS steels offer the promise of higher operating temperatures, they are produced by complicated and expensive mechanical-alloying, powder-metallurgy techniques. Therefore the need exists for elevated-temperature steels with higher operating temperatures that can be produced by conventional processing techniques (i.e., melting, casting, hot working, cold working, etc.). Based on the science of precipitate strengthening (the need for large numbers of small precipitate particles) and with the aid of thermodynamic modelling to choose optimum compositions, a thermomechanical treatment (TMT) process was developed at Oak Ridge National Laboratory (ORNL) that increased the 0.2% yield stress of commercial nitrogen-containing 9% and 12% Cr martensitic steels (modified 9Cr–1Mo, NF616, and HCM12A) by over 135% at 700 °C [39]. Steels designed and produced specifically for the TMT have yield stresses at 700 °C up to 200% greater than conventional normalized-and-tempered steels. Steels were produced with strengths as good as the strength of one of the strongest experimental ODS steels (heat 12YWT) with similar ductility. Preliminary creep-rupture tests on 9Cr–1Mo modified by this process indicated a commensurate increase in rupture life.

Precipitate strengthening in conventional normalized-and-tempered ferritic/martensitic steels derives from fairly large (average size ≈ 32 nm) MX particles at a relatively low number density ($\approx 8 \times 10^{18}\ m^{-3}$). Characterization of MX precipitates in the new steels by transmission electron microscopy (TEM) and atom probe tomography indicated that, depending on the TMT and composition, the nano-sized precipitates could be up to eight-times smaller (≈4 nm) at a number density almost four orders of magnitude greater ($7 \times 10^{22}\ m^{-3}$) than in the conventional steels.

3. Summary

A number of high dose irradiation experiments have been recently completed. They include fast neutron irradiations and irradiations with a mixed spectrum of high-energy protons and spallation neutrons allowing for enhanced helium and hydrogen production rates. Most corresponding PIEs are still in progress. They should be completed in the next two or three years. Preliminary results confirmed the occurrence of typical irradiation-induced embrittlement effects, including radiation hardening (in tensile tests), loss of ductility, increase in the DBTT and loss of fracture toughness. For irradiation temperatures of about 300 °C, the radiation hardening and DBTT shift show a tendency to saturation with increasing dose. However, eventual full and complete saturation at high doses still requires further confirmation.

Other promising on-going activities relate to the manufacture of Fe-54 EUROFER 97 specimens, allowing for enhanced helium production rate under neutron irradiation (still far below the rate expected to occur in fusion systems, however), and to the modelling of radiation damage and radiation effects as a function of temperature, accumulated damage, damage rate, and He/dpa and H/dpa production rates.

The present coverage of different RAFM steel products (plate, powder HIPped steel, many types of fusion and diffusion welds, unirradiated and irradiated states) is sufficient to present a strong case for the use of RAFM steels in ITER test blanket modules.

For application in DEMO much more effort is needed, including the use of IFMIF in order to quantify the effects of large amounts of transmutation products such as helium and hydrogen.

Technological issues that still require additional information relate in particular to the assessment of irradiation-induced changes in mechanical properties (tensile, fracture toughness, creep, fatigue) for ITER TBM and DEMO relevant conditions, compatibility with possible coolants and breeding materials (flowing Pb–Li, solid ceramic breeding materials, hot water), development of reliable joints, development of corrosion and permeation barriers, development and/or validation of design rules (e.g. creep-fatigue-interaction rules), and lifetime assessment of TBMs.

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