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Current status and recent research achievements in ferritic/martensitic steels

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ABSTRACT

When the austenitic stainless steel 316L(N) was selected for ITER, it was well known that it would not be suitable for DEMO and fusion reactors due to its irradiation swelling at high doses. A parallel programme to ITER collaboration already had been put in place, under an IEA fusion materials implementing agreement for the development of a low activation ferritic/martensitic steel, known for their excellent high dose irradiation swelling resistance. After extensive screening tests on different compositions of Fe–Cr alloys, the chromium range was narrowed to 7–9% and the first RAFM was industrially produced in Japan (F82H: Fe–8%Cr–2%W–TaV). All IEA partners tested this steel and contributed to its maturity. In parallel several other RAFM steels were produced in other countries. From those experiences and also for improving neutron efficiency and corrosion resistance, European Union opted for a higher chromium lower tungsten grade, Fe–9%Cr–1%W–TaV steel (Eurofer), and in 1997 ordered the first industrial heats. Other industrial heats have been produced since and characterised in different states, including irradiated up to 80 dpa. China, India, Russia, Korea and US have also produced their grades of RAFM steels, contributing to overall maturity of these steels. This paper reviews the work done on RAFM steels by the fusion materials community over the past 30 years, in particular on the Eurofer steel and its design code qualification for RCC-MRx.

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1. Introduction

Fusion structural materials activities have evolved over the past four decades, maturing with time and becoming design oriented and lately achieving code qualified status [1]. At the beginning, in the early 80s, the activities were performed at laboratory or national levels and often on small melts. With the start of international collaborations, such as for the NEXT machine in Europe, these activities began to converge and follow a common objective. With the ITER agreement, fusion materials activities were separated in two branches, one following ITER objectives and other dealing with beyond ITER (DEMO and Power Reactors). The latter activities were mostly grouped under an IEA fusion materials implementing agreement/Annex II; less formal and more open to new partners than ITER, although the initial members were the same as ITER.

Early inputs to ITER and IEA activities were largely brought from the fission program [2,3]. In fact, most of the fusion material specialists were former fission specialists that had collaborated under different fission international programs, e.g. the European Fast Reactor (EFR) program. However, fusion established from the beginning its distinctive mark «Low Activation» and with the lull in fission activities became the driving force for development of structural materials for nuclear applications.

ITER materials activities were largely influenced by its time schedule. Advanced low activation materials such as vanadium alloys and SiC_f/SiC composites, and even martensitic steels were discarded in favour of the more robust stainless steel type 316L(N), with proven service experience in several generations of Fast Breeder Reactors (FBRs) [2]. In fact, 316L(N)-IG chosen for ITER is a derivative of 316L(N)-SPH used in the Superphénix and retained for the EFR [2,4]. DEMO materials activities did not have the same time constraint and in addition it was well known that the solution annealed austenitic stainless steels such as 316L(N) are not suitable for high dose applications (in DEMO > 70 dpa) due to their irradiation swelling [2,5]. Vanadium alloys and SiC_f/SiC composites developments lasted several years under the IEA

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collaboration but finally were marginalised due to several unresolved shortfalls (e.g. low temperature irradiation embrittlement and absence of reliable protective coating for vanadium alloys [6], and low thermal conductivity and low fracture toughness for SiC_f/SiC [7]). The bulk of IEA collaboration from the beginning went on the martensitic steels [8] with precursor work in several member countries, e.g. Manet and Optifer in EU [9,10].

This paper presents the work done from early stages of RAFM steels development to their more recent qualification for reactor design codes [11–20]. Aspects related to higher helium to dpa generated in fusion environment are left out since they are still under investigation and not ready to be integrated in design codes. An excellent review of the effects of helium in irradiated structural alloys is given in [21].

2. Materials

As mentioned in the introduction, initial inputs to fusion program were strongly influenced by the fission experience. Nevertheless, extensive screening tests were performed on different Fe–Cr compositions before narrowing down the chromium range to 7–9% and finally converging towards a composition similar to that of the conventional Modified 9Cr–1Mo steel. Fig. 1 shows an example of the results after irradiation in FFTF at 365 °C to 7 dpa, where the changes in DBTT of 7–9%Cr alloys are smaller (results compiled from presentations at an IEA topical meeting).

In 1995, IEA/Annex II defined a reference low activation steel to be produced in Japan and characterised by all members. The term RAF/M (Reduced Activation Ferritic/Martensitic) steel was used instead of LAF/M (Low Activation F/M Materials) to distinguish these grades from the ultimate low activation materials that will push concentrations of high activation residual elements even lower. Two industrial heats were fabricated (Fig. 2) and designated IEA-F82H heats, to distinguish them from an earlier F82H heat, also produced in Japan (called Pre-IEA F82H) [10].

The IEA heats were characterised by all partners and the results were collected and after validation entered in dedicated relational databases that were then used to derive F82H design allowables. In parallel, several IEA partners continued work on other RAFM grades including JLF1 and JLF2 in Japan [13]. In 1997, EU opted for a higher chromium and lower tungsten composition grade, Eurofer (also called Eurofer97), to improve corrosion resistance and neutron efficiency [14]. From the beginning an industrial specification was used for production of Eurofer steel [22]. Other countries, China (CLAM: Chinese Low Activation Material), India (INRAFM: Indian Reduced Activation Material), Korea (ARAA: Advanced Reduced Activation Alloy) are investigating similar compositions and targeting industrial productions for ITER TBMs. Limited work has also been going on in Russia (RUSFER: Russian Reduced Activation Material). United States and in particular ORNL have been pursuing basic studies to develop RAFM steels with higher strength and improved radiation resistance with applicable temperatures up to 600–650 °C. Additional information of above work can be found in [14–20].

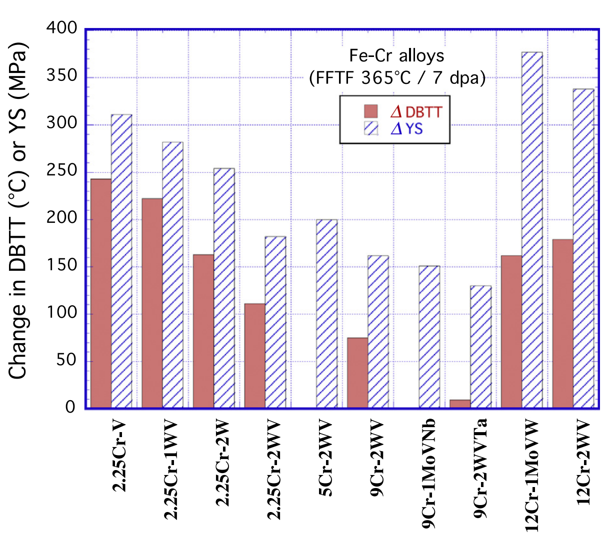

Fig. 1. Effect of irradiation on ductile-to-brittle transition temperature (sub-size specimens) and yield stress of Fe–Cr alloys.

Table 1 presents chemical compositions of four RAFM steels produced in different countries along with the composition of the conventional Modified 9Cr–1Mo steel. The basic difference between RAFM steels and the conventional steel is in replacement of Mo and Nb with their equivalent low activation elements (W and V) [14]. Other high activation residual elements are kept as low as possible. Tantalum is added for grain size control.

Heat treatment specifications and acceptance values of RAFM steels are similar to the conventional 9Cr–1Mo steels [3]. However, while Modified 9Cr–1Mo steel has long been design code qualified, most of the RAFM steels are still in the development stage, except F82H and Eurofer steels. Eurofer achieved code qualification status after 30 years in 2013 with its entry in RCC-MRx edition 2012 (under Section III, Tombe 1, Sub-Section Z and denomination A3.19AS)[1]. F82H is expected to follow with its entry in the Japanese codebook.

3. Databases

An important distinction is to be made between general material's properties data and the code-qualified materials properties data [23–27]. In the case of code-qualified properties, all data collected must be harmonised and validated by expert groups before they are entered in the databases. In addition, each datum point must be obtained according to an internationally accepted procedure and should be fully traceable back to its origin and experimental and testing history. For instance, all specimens taken from F82H sub-products dispatched to laboratories are linked to the production route shown in Fig. 2.

In the early stages of design, e.g. conceptual design analysis, the above requirements were relaxed and missing information about some properties were taken from not fully qualified sources. However, in the detailed design analysis stage and later for engineering design analysis, all data used were "code-qualified". As a result, the quality of materials properties data collected in the fusion program has varied with time. For instance, materials properties data from the literature were initially included in the ITER MPH (Materials Properties Handbook) to allow conceptual design analysis to proceed [4]. For the ITER Interim Structural Design Analyses (ISDC) only the code-qualified part of the data was used [28]. Recent updates of MPH have been harmonised with SDC-IC (formerly ISDC) and contain mostly code-qualified data. For a fuller insight into the procedures required for code qualification, the reader is referred to EU CEC works carried out on different properties of 316 and Mod. 9Cr–1Mo steels under EFR contracts and used to revise RCC-MR design allowables. An example of this is available in [29] for fatigue properties.

All Eurofer data entered in the EU databases are now code qualified. Extracts from these databases are used at first to derive design allowables for ITER Test Blanket Modules (TBMs), since TBM design is in an advanced stage, its construction schedule is close (2020) and does not require irradiation data higher than 3 dpa. For DEMO

[1] RCC-MRx is a new French reactor construction code combining RCC-MR and RCC-Mx and includes fusion materials.

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