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Material science and manufacturing of heat-resistant reduced-activation ferritic–martensitic steels for fusion

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Abstract

A number of issues regarding the development and use of 10–12% Cr reduced-activation ferritic–martensitic steels (RAFMS) for fusion are considered. These include: (1) problems of manufacturing and modifying their composition and metallurgical condition; (2) the influence on properties of their composition, purity, δ-ferrite concentration and cooling rates in the final stages of manufacturing; and (3) the effects of neutron irradiation at 320–650°C up to 108 dpa on their mechanical properties. In addition, neutron activation and nuclear accumulation of elements in RAFMS with different initial concentrations of alloying and impurity elements for typical fusion reactor (DEMO) irradiation regimes have been calculated.

1. Introduction

10–12% Cr ferritic–martensitic steels are being considered as structural materials for the DEMO fusion reactor (first wall and blanket). Attractive features of these steels include their high yield strength and adequate ductility combined with a favorable combination of physical properties and irradiation resistance in the temperature range of 300–650°C [1]. The analysis of DEMO reactor component operation in this temperature range in neutron fluences up to 200 dpa under conditions of cyclic loading up to 10^5 cycles shows that ferritic–martensitic steels will have to be resistant to thermal cycling, irradiation and corrosion as well as radioactivation; to meet the latter requirement the steels must contain limited quantities of Nb, Mo, Ni, Cu and Ag [2,3]. This combination of requirements drastically narrows the range of compositions. Therefore, the main focus of this study is on steels that have already demonstrated high performance as structural materials for fuel rod cladding, fuel assembly wrappers and other components of experimental and commercial fast reactors (BN-600, BN-350, BOR-60). These are primarily the 12% Cr steels EP-450 and EP-823, which are shown in Table 1.

2. Irradiation properties

Compared to austenitic Cr–Ni steels, the substantial advantage of ferritic–martensitic steels is their low swelling at doses up to 100 dpa in a wide temperature range, T_{irr}. For example, the irradiation-induced swelling of EP-450 steel is 0.1% at 90 dpa and $T_{irr} = 400°C$ [4]. Another favorable feature of ferritic–martensitic steels is that they are not prone to high-temperature embrittlement.

The common limitation inherent in these steels is their propensity toward irradiation-induced embrittlement, which shows up both as an upward shift in the ductile–brittle transition temperature and as lower val-

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Table 1
Chemical composition of ferritic–martensitic steels

Grade of steel	Content of elements (% mass)									
	C	Si	Ni	Cr	V	Mo	W	Nb	B	Ta
EP-450 (1Cr12Mo2NbVB)	0.10–0.15	<0.5	0.05–0.30	11.0–13.5	0.1–0.3	1.2–1.8	–	0.3–0.6	0.004 (calculated)	–
EP-823 (16Cr12MoWSiVNbB)	0.14–0.18	1.1–1.3	0.5–0.8	10.0–12.0	0.2–0.4	0.6–0. 9	0.5–0.8	0.2–0.4	0.006 (calculated)	–
16Cr12W2VTaB (Reduced activation)	0.10–0.20	0.3–0.5	0.01–0.5	10.0–12.0	0.5–1.0	⩽0.01	1.0–2.0	⩽0.01	0.003–0.006	0.1–0.2

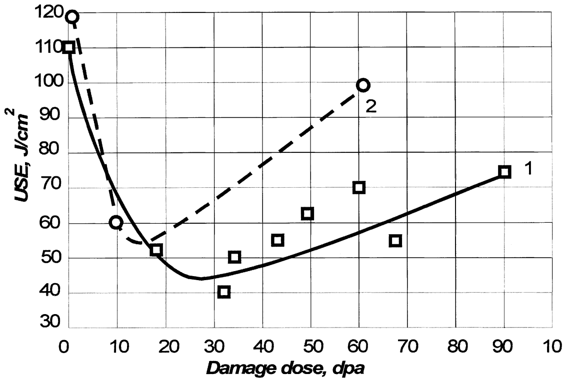

Fig. 1. Effect of damage dose on USE of the 1Cr12Mo2NbVB (1) and 16Cr12MoWSiVNbB (2) steels used as wrapper material in subassemblies and irradiated at 350–365°C.

ues of fracture toughness and ductility. Under irradiation, a hardening effect is observed in the steels under study that is particularly prominent at low irradiation doses (10–30 dpa) in a narrow temperature range (300–365°C). As the dose is increased, the initial strength is partially recovered [2]. A similar dependence is also observed for the toughness. After a substantial reduction at doses of 10–30 dpa, the toughness (the upper shelf energy, USE) starts increasing with dose (Fig. 1). The recovery of ductility is observed to occur to a lesser extent [4–7].

Evidence suggests that the propensity of Cr steels toward irradiation-induced embrittlement is substantially affected by their δ-ferrite content (Fig. 2). A higher purity metal, obtained by a combination of the use of purer (fresh) charge materials and electric slag remelting applied after open smelting in air, also diminishes the magnitude of the shift of the ductile–brittle transition

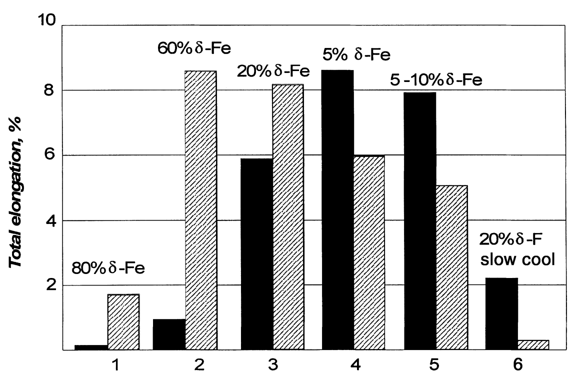

Fig. 2. Total elongation of 12% Cr steels containing different amounts of δ-ferrite as BOR-60 irradiated at 345–365°C, to the fluence of 2.7×10^{26} neutrons/m^2. ■ – $T_{test} = 20°$, ▨ – $T_{test} = 365°$.

temperature of Cr steels [1,8]. The fabrication process parameters for Cr steel products can also have a substantial effect on their embrittlement. For example, reducing the cooling rate of steels with a limited δ-ferrite content (⩽20%) from 50–100°C/min to 1–2°C/min drastically reduces their ductility (Fig. 2) [6]. This must be taken into account in the development of fabrication processes for tubing, sheet and other items for DEMO modules.

At irradiation temperatures of 380–500°C and doses up to 108 dpa, 12% Cr steels are observed to harden slightly; their ductility rises monotonically and embrittlement is not manifest. This behavior is shown in the results obtained for EP-823 and EP-450 irradiated in BN-600 at $T_{irr} = 385$–500°C to a neutron dose of 60–108 dpa [2,9]. The hardening of EP-823 is not substantial, and up to 600°C, the ductility of the material does not show substantial changes compared to its initial condition; however, at $T > 650$°C, the ductility increases sharply. No indications of embrittlement are observed, and this is corroborated by both microstructural and fractographic analyses.

Fig. 3 compares the thermal and in-reactor creep strains of internally pressurized tube specimens of EP-450 steel as a function of stress at test temperatures of 480°C, 500°C, 630°C and 700°C. In the temperature range from 480°C to 500°C and at stresses from 98 to 196 MPa, there is little difference between the thermal and in-reactor creep strains. However, as the stresses increase to 294 MPa, there appears to be an irradiation hardening effect, as the in-reactor creep strain ($\Delta d/d = 0.5$–1.0%) becomes lower than the thermal creep strain ($\Delta d/d = 2.3$%). At the higher test temperatures of 630–700°C, some irradiation-enhanced creep is apparent.

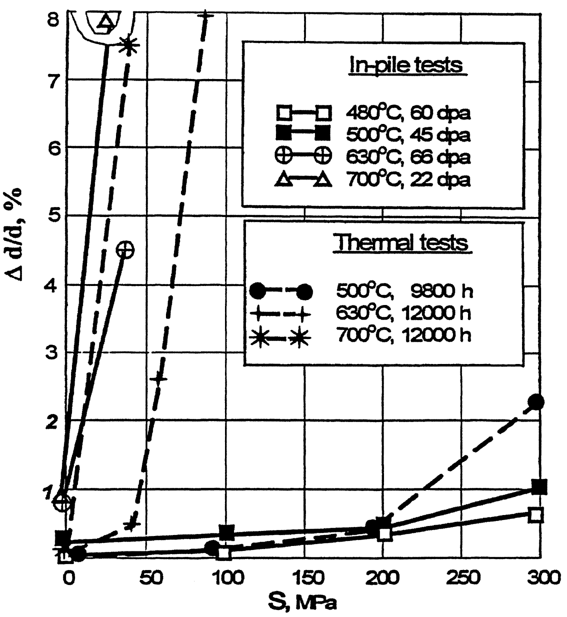

Fig. 3. Influence of temperature and stress on deformation effected by thermal and in-pile creep of EP-450 steel △: ↑ 11.4%.

3. Reduced-activation modification of 12% Cr steel

The previous discussion refers to steels that are not optimized in their composition for reduced activation. In our approach to designing similar reduced-activation steels, we have proceeded to reduce the concentrations of Mo, Nb, Ni and other elements which adversely affect activation, while attempting to retain the good high-temperature performance and irradiation resistance of this class of steels. Table 1 lists the composition of a reduced-activation analogue of EP-823.

This composition was used as the basis in a computational exercise to estimate the long-term activity of this steel following operation in a fusion reactor as a first wall. This was part of a larger exercise to evaluate induced activity of candidate materials for fusion reactors [10–13]. In this study, two variations of the steel composition were evaluated. These are designated as A-min and A-max and correspond to the maximum and minimum alloying concentrations shown in Table 1. The FENDL/A-2 base library of nuclear cross-sections was used. The source library FENDL/A-2.0 was taken in a 175-group approximation (VITAMIN-J division) and reduced to a single group representation of the DEMO reactor neutron spectrum. Radioactive decay was calculated on the basis of the FENDL/D-2.0 library of properties of radioactive nuclei. The transmutation and induced activity were computed using the program FISPACT-3.0(5) on a 1 kg basis. In this work, variations in the nuclide composition of the samples were investigated at a fixed neutron load of 12.5 MWy/m^2 followed by cooling up to 1000 yr.

The results are shown in Fig. 4 and Table 2. Fig. 4 shows the dose rate from various species as a function of decay time as well as the total for both compositions, from which the following points can be made:

- the level of the total dose from the induced activity of steel diminishes at a relatively high rate; after a month, it is 400 Sv/h, and after a year, it is 90 Sv/h. However, the total dose will be reduced to a low level (10 mSv/h) after 50–60 yr;
- the total irradiation dose from induced activity differs little between the minimum and maximum contents of steel elements, and the difference essentially disappears after 10 yr;
- the main contribution to the induced activity 1 m and 1 yr after shut-down comes from Fe-55, Ta-182, Mn-54 and Co-60 and after 10 yr, from Fe-55 and Co-60.

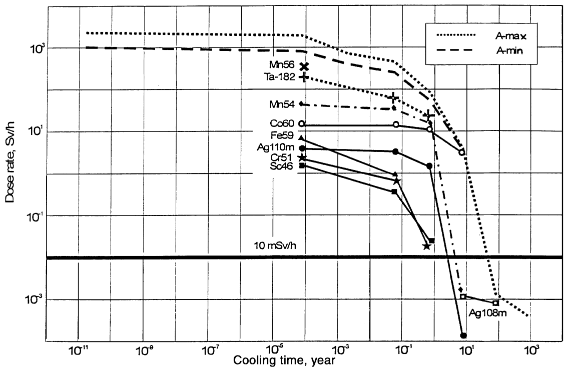

Fig. 4. Time dependence of γ-radiation accumulated dose rate (Sv/h) for steel 16Cr12W2VTa.

The contribution to the total irradiation dose from the induced activity comes from Ta-182, Mn-54 and Co-60 (up to 1 yr cooling after irradiation) and from Co-60 after up to 10 yr.

Table 2 shows the variation in transmutant content with time for the two steel compositions, from which the following points can be made:

- under irradiation, gaseous products (He and H) are formed in steel; at the maximum alloying element content, the build-up proceeds at a high rate;
- irradiation does not essentially affect variations in the concentrations of oxygen and nitrogen (or sulfur or phosphorus, not shown); hence, the influence of these elements on the properties of the steels will be governed by their initial concentrations;
- irradiation of these steels results in the formation of low-melting metals such as Li, Cd, Mg and Zn. This primarily shows up in the steel with the maximum concentration of alloying elements. The total content of the above low-melting elements may reach $\sim 1 \times 10^{-3}$ wt%. The influence of this effect on the performance of steel requires additional investigation.

4. Conclusions

10–12% Cr ferritic–martensitic steels have attractive properties for application to the first wall and blanket of a fusion reactor. The level of commercial application and experience gained in fast reactor operation with EP-450 and EP-823 suggests that their reduced-activation analogue (16Cr12W2VTaB) that is under development at SSC RF-VNIINM has significant promise.

The resistance of 12% Cr steels to low-temperature irradiation embrittlement can be improved by: (1) a reduction in the content of deleterious impurities (low-melting metals, S, P and O) by the use of high-purity charge materials and vacuum methods of melting and remelting; (2) optimization of the initial structure and condition of the steel (δ-ferrite content, grain size, morphology of phases and grain boundary condition); and (3) higher cooling rates ($\geqslant 50$°C/min) of products following final heat treatment.

In-reactor creep of 12% Cr steels has exhibited several regimes. At 480–500°C, both thermal and in-pile creep take place; however, the rate of thermal creep is ~ 2.5 times higher. At 630°C and 700°C, the rates of thermal and in-pile creep are large, and the in-reactor creep rate is larger than the thermal creep rate.

Calculations show that the reduced-activation steel 16Cr12W2VTaB will be activated in a DEMO fusion reactor spectrum. The main contribution to the induced activity of this steel comes from Fe-55, Ta-182, Mn-54 and Co-60. A low level (10 mSv/h) of the total irradiation dose is reached in 50–60 yr after irradiation at to 12.5 MWy/m^2. During this irradiation, the concentrations of elements such as Cr, W, Ta, V, C, S, P, O and N do not significantly change. However, transmutant gases (H and He) and low-melting metals (Li, Mg, Zn and Cd) increase in concentration with irradiation time and depend on the concentrations of the alloying elements.

Table 2
Variations in concentrations of some elements in steel 16Cr12W2VTaB at minimal (A-min) and maximal (A-max) initial contents of alloying elements (Table 1)

Content of initial elements	Time of irradiation (yr)	Content of elements (% mass $\times 10^5$)							
		O	N	H	He	Li	Mg	Zn	Cd
A-min	0	100	5000	–	–	–	–	–	–
	2.5	99.9	4992	3.96	3.16	1.3	0.45	0.12	25
	6.0	99.9	4991	10.44	5.04	3.0	1.1	0.29	58
	10	99.9	4990	18.0	8.64	4.6	1.8	0.48	93
A-max	0	100	5000	–	–	–	–	–	–
	2.5	99.9	4992	4.32	6.48	8.0	0.6	1.2	25
	6.0	99.9	4991	10.80	14.40	18	1.5	2.9	58
	10	99.9	4990	18.36	23.04	27	2.5	4.8	93

The influence of these elements on the irradiation-induced property changes of these steels requires further investigation.

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