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CORROSION BEHAVIOR OF RAFM STEELS IN PRESSURIZED WATER FOR FUSION APPLICATIONS

D. De Meis, E. Lo Piccolo, R. Torella

Riassunto

L'acciaio inossidabile austenitico AISI 316 L(N) IG è utilizzato come materiale strutturale per i principali componenti in-vessel di ITER. Quando i flussi neutronici aumentano come nei componenti in vessel di DEMO, non è possibile utilizzare l'AISI 316, in quanto è soggetto a forte attivazione a causa dell'elevata presenza di Nichel. Devono essere previsti acciai ferritici/martensitici ad attivazione ridotta come l'Eurofer97 che mantengono buone proprietà termo-meccaniche e stabilità dimensionale sotto irraggiamento (i.e. resistenza al rigonfiamento). Gli acciai ferritici/martensitici con 9%Cr a ridotta attivazione (RAFM) hanno una più elevata conducibilità termica, più basso coefficiente di espansione termica, una più bassa suscettibilità alla tensocorrosione, migliore resistenza al danneggiamento neutronico e ridotto rigonfiamento da irraggiamento rispetto agli acciai inossidabili austenitici. Tuttavia gli acciai ferritici/martensitici hanno delle limitazioni dovute agli alti tassi di corrosione, bassa resistenza al creep alle alte temperature e infragilimento da irraggiamento a basse temperature.
In questo lavoro viene messo in evidenza lo stato dell'arte circa la corrosione generalizzata e la corrosione sotto tensione degli acciai ferritici/martensitici in acqua pressurizzata per applicazioni fusionistiche. Il documento riporta la perdita di peso a causa della corrosione degli acciai ferritici/martensitici RAFM. Un adeguato controllo della chimica dell'acqua è in grado di sopprimere il verificarsi della corrosione sotto tensione in un acciaio tipo Eurofer97 sottoposto ad irraggiato neutronico.

Parole chiave: Eurofer97, RAFMS, corrosione uniforme, SCC, DEMO

Abstract

The austenitic stainless steel AISI 316 L(N) IG is used as structural material for the main ITER in-vessel components. When neutron fluences increase, as in DEMO in-vessel components, it is not possible to use AISI 316, which is subject to strong activation due to its high nickel content. Ferritic/martensitic steels with reduced activation properties as Eurofer97 which keep good thermo-mechanical properties and good dimensional stability under irradiation (i.e. resistance to swelling), must be envisaged.
Reduced activation 9%Cr ferritic/martensitic steels (RAFM) steels have higher thermal conductivity, lower coefficient of thermal expansion, lower susceptibility to SCC (Stress Corrosion Cracking), better resistance against neutron irradiation damage and reduced swelling under irradiation compared with austenitic stainless steels. However RAFM steels have limitation due to high corrosion rates, low creep strength at high temperatures, and radiation embrittlement at low temperature.
In the present paper is showed the current status about the uniform corrosion and SCC of RAFM steels in pressurized water for fusion applications. The paper reports the weight loss because of corrosion of RAFM steels. Proper water chemistry control is able to suppress SCC in irradiated Eurofer97.

Keywords: *Eurofer97, RAFMS, uniform corrosion, SCC, DEMO*

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1. Introduction

Eurofer is the low activation version of 9%CrMoVNb (T91) RAFM steels developed for steam generator units in conventional power plant: Mo, Nb substituted with W, Ta.

RAFM steels have higher thermal conductivity, lower coefficient of thermal expansion, lower susceptibility to SCC, better resistance against neutron irradiation damage and reduced swelling under irradiation compared with austenitic stainless steels (Maday, 2014).

The good thermal conductivity and the low coefficient of thermal expansion ensure high heat transfer and resistance to thermal shocks/thermo mechanical stresses.

The maturity of the RAFMs as structural material is currently way beyond the others, especially from the point of manufacturing techniques, industrial productivity, material database, total-performance and so on. The chemical compositions of the ferritic-martensitic steels are shown in table 1.

However RAFM steels have limitation due to high corrosion rates, low creep strength at high temperatures, and radiation embrittlement at low temperature (Ampornrat, 2009).

It seems that water-cooled components of RAFM steels could be safely operated, at least under proper coolant chemistry control and low-to-moderate dose neutron irradiation (Féron, 2012).

wt.%	C	Si	Mn	Cr	W	V	Ta	Mo	Ni	Nb
F82H	0.09	0.13	0.16	7.7	1.95	0.16	0.04	–	0.04	–
JLF-1	0.1	<0.1	0.46	9.04	1.97	0.2	0.07	<0.01	–	–
EUROFER 97	0.1	0.05	0.44	8.8	1.15	0.2	0.07	0.003	–	0.002
Optifer Ia	0.11	0.06	0.57	8.5	1.16	0.23	0.07	0.005	0.005	0.009
1.4914	0.13	0.37	0.82	10.6	–	0.22	–	0.77	0.87	0.16
FTT-9	0.2	0.22	0.5	11.8	0.5	0.29	–	0.99	0.48	–

Table: 1 The chemical compositions of the ferritic-martensitic steels (Kimura 2006)

2. Uniform corrosion of RAFM steels in pressurized water

The RAMF steel can be included in the high alloyed steels family and its behavior to corrosion attack is similar to the carbon steels. The content of chromium in the alloy is not enough to guarantee a stable passive film of Cr/CrO_x, and, therefore, an active state of the surface is obtained in acid condition.

The pH should be stabilized under a range between 7-8, where the RAMF materials is under passive state. In fact RAMFS is in active state below pH 7. Passive state, constituted by magnetite, is obtained under pH higher than 7 (typically 7.4-8). Such condition constituted a safety condition in term of susceptibility to uniform corrosion attack.

Due to the above mentioned scenario, the importance a strictly control of the water chemistry in the PWR apparatus is extremely important. Water pH should be maintained as much a possible under stable condition by a suitable buffer system, which is related to water chemistry control.

Fig. 1 shows the passive current density in high-pressure water at 523 K in order to investigate the corrosion resistance of ferritic–martensitic steel.
The above mentioned figure indicates that corrosion resistance remarkably depends on the chromium concentration. In comparison with an austenitic stainless steel (SUS304), the ferritic steels containing 9–10% Cr showed five times larger current density, namely higher corrosion rate.
As it is well known the increase in the Cr concentration improves corrosion resistance but decreases fracture toughness, with and without irradiation. However, irradiation experiments showed that the embrittlement became a minimum at the Cr concentrations ranging from 7 to 9%. (Kimura, 2006).

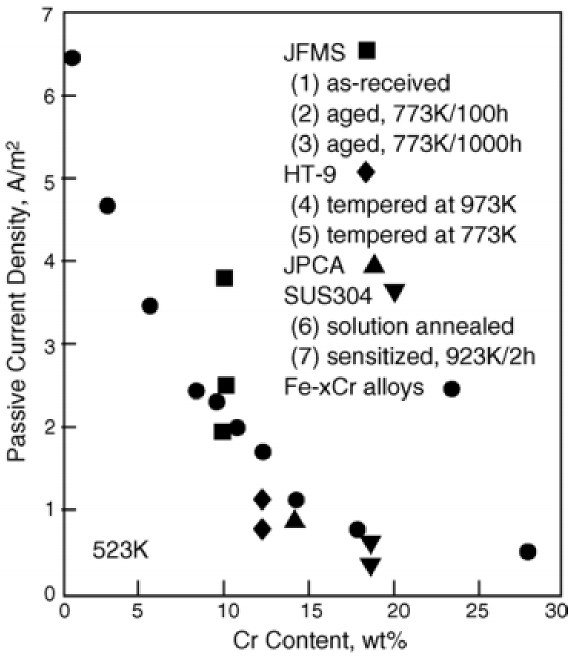

Figure: 1 Dependence of corrosion rate in pressurized water at 523 K on the Cr content of the steels and Fe-Cr alloys (Kimura, 2006)

The uniform corrosion tests showed that the weight loss of F82H steel was 60 mg/dm^2 at 533 K for 2600 h and 30 mg/dm^2 at 500 h (see fig. 2) (Kimura, 2006; Lapena, 2000).

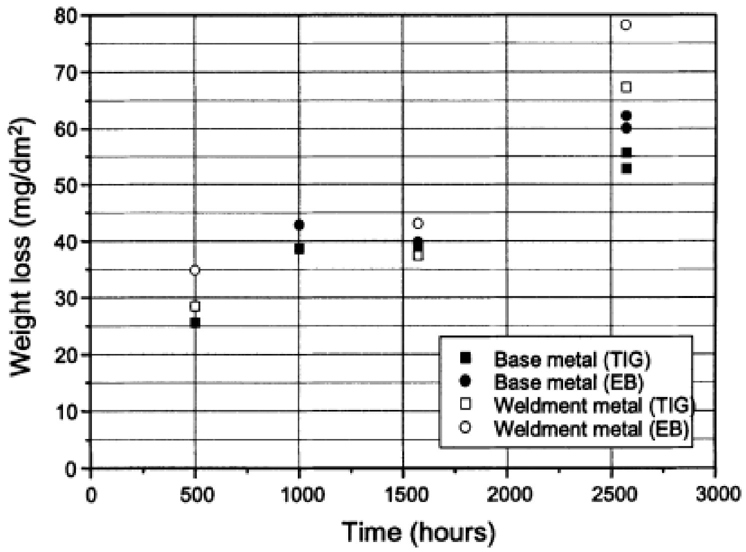

Figure: 2 Weight loss versus time for base and weld material (Lapena, 2000)

Nakajima (2015) reports the effects of water flow and dissolved oxygen (DO) on corrosion behaviour of reduced activation ferritic/martensitic steel, F82H. The corrosion tests were performed in high temperature pressurized water by using a test apparatus for rotated disk sample. All of specimens showed weight gains after static corrosion tests up to 500 h. However, the rotated disk showed weight losses except for test in the water with DO=8 ppm, and the weight loss was significant with lowering DO concentration.

3. Environment assisted cracking of RAFM steels in water

SCC is the combined action of stress and corrosive environment which leads to the formation of a crack which would not have developed by the action of the stress or environment alone. SCC is a problem because it can happen unexpectedly after a period of satisfactory service. Typically SCC failures are seen in pressure vessels, pipe-works, highly stressed components and in systems when an quick change from normal operating conditions or the environment occurs.

Irradiation assisted stress corrosion cracking (IASCC) in the RAFM steels with water cooling in the 285-325˚C regime is a potential threat. Although very few studies have been conducted, there is evidence for the susceptibility of the RAFM steels to IASCC for certain combinations of material compositions, irradiation parameters and environmental conditions (Tillack, 2014).

The occurrence of environmentally assisted cracking (EAC) depends on both the environment and material conditions. For nuclear applications both are subject to modifications due to irradiation.

The influence of irradiation on the stress corrosion cracking behaviour of Eurofer97 in water have shown an increase in potential and corrosion rate (Van Dyck, 2005). The paper of Van Dyck demonstrates that proper water chemistry control is able to suppress the occurrence of SCC in irradiated Eurofer97.

Hirose reports that F82H (reduced activation ferritic/martensitic steel) has been tested trough slow strain rate tests (SSRT) in super-critical pressurized water (SCPW) and didn't demonstrate stress corrosion cracking. The corrosion rate of F82H in SCPW is estimated to be 0,04 mm/year (Hirose, 2007).

Miwa, in order to evaluate SCC susceptibility of F82H, has done slow-strain-rate test (SSRT) at different temperatures in oxygenated or hydrogenated water. It was found in irradiated specimen, TGSCC (trans granular SCC) occurred when SSRT was conducted at 573 K in hydrogenated water (dissolved Hydrogen=1 ppm) or when the notched specimen was tested by SSRT at 573 K in oxygenated water (dissolved oxygen =10 ppm) (Miwa, 2009).

Jitsukawa reports that susceptibility for environmentally assisted cracking for martensitic steels is not believed to be an issue. Figure 3 shows the engineering stress-strain curves for irradiated and un-irradiated F82H specimens in high-temperature water environments. No evident effect of irradiation on the curves were observed (Jitsukawa, 2004).

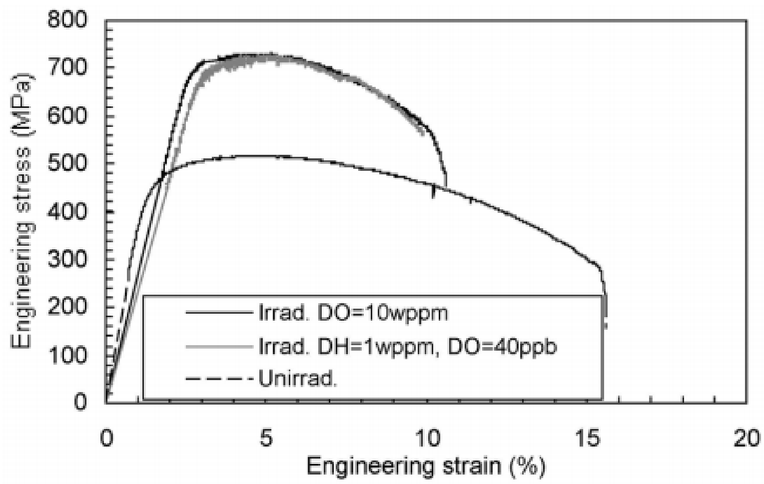

Figure: 3 Engineering stress-strain relations for SSRT tests performed in high-temperature water environments (Jitsukawa 2004).

4. Conclusions

Compared with austenitic stainless steels RAFM steels have higher thermal conductivity, lower coefficient of thermal expansion, lower susceptibility to SCC, better resistance against neutron irradiation damage and reduced swelling under irradiation.

In comparison with an austenitic stainless steel, the ferritic steels containing 9–10% Cr, showed the five times larger current density, namely higher corrosion rate (Kimura 2006).

The uniform corrosion test results showed that the weight loss of a RAFM, F82H, was 6 g/m^2 at 533 K for 2600 h (Kimura, 2006; Lapena, 2000).

The influence of irradiation on the stress corrosion cracking behavior of Eurofer97 in water have shown an increase in potential and corrosion rate (Van Dyck, 2005). Van Dyck concludes that proper water chemistry control is able to suppress the occurrence of SCC in irradiated Eurofer97.

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