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STRUCTURAL MATERIALS FOR DEMO

DOMENICO DE MEIS

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RT/2015/25/ENEA

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Sommario
Con la costruzione di ITER, attualmente in fase avanzata, l'attenzione è ora posta alla progettazione del futuro reattore: l'impianto dimostrativo di produzione di energia a fusione denominato DEMO. DEMO sarà il prossimo progetto di reattore a fusione in grado di produrre 500 MW di potenza elettrica netta, funzionante con un combustibile a ciclo chiuso. Esso sarà l'ultimo impianto realizzato dopo ITER e prima del reattore commerciale previsto per il 2050 (1, 2, 3).
Per i componenti principali in-vessel di ITER (ad esempio il divertore, il mantello schermante, i port plugs, ecc.) è stato utilizzato come materiale strutturale l'acciaio inossidabile austenitico AISI 316 L (N) IG. Quando il danneggiamento nucleare aumenta, come nel TBM (Test Blanket Module) di ITER o nei componenti in-vessel di DEMO, non è possibile utilizzare l'AISI 316 ma deve essere previsto un materiale come l'Eurofer con basse proprietà di attivazione e buona resistenza al danneggiamento neutronico.
L'obiettivo principale del presente lavoro è quello di studiare il comportamento meccanico di tutti i possibili materiali strutturali che possono essere utilizzati per i componenti in-vessel. Particolare attenzione sarà posta sull'acciaio Eurofer.

Parole chiave: Eurofer, AISI 316, DEMO, materiale strutturale

Abstract
With the construction of ITER well underway, attention is now posed to the design of a successor device: a future fusion energy generation Demonstration Fusion Power Plant (DEMO). DEMO will be the nearest-term fusion reactor design capable of producing net electricity power of 500 MW, operating with a closed fuel-cycle and being a single step between ITER and a commercial reactor foreseen by 2050 (1, 2, 3).
For the main ITER in-vessel components (e.g. divertor, shielding blanket, port plugs, etc.) the austenitic stainless steel AISI 316 L(N) IG has been used as structural material. When the nuclear damage increases, as in ITER TBM (Test Blanket Module) or in DEMO in-vessel components, it is not possible to use AISI 316 but material with low activation properties and good resistance to neutron damage as Eurofer must be foreseen.
The principal objective of the present paper will be to study the mechanical behavior of all possible structural materials that can be used for in-vessel components. In particular, focus will be put on Eurofer steel.

Keywords: *Eurofer, AISI 316, DEMO, structural material*

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1. Introduction

Reduced Activation Ferritic Martensitic (RAFM) steel is the primary choice material for first wall and breeding blanket structural application for future fusion power plants. These steels have been developed in order to simplify special waste storage of highly radioactive structures of fusion reactor after service. With this objective some alloying elements such as Mo, Nb and Ni present in the commercial martensitic steels have been replaced by other elements which exhibit faster decay of induced radioactivity such as Ta, W and V. Eurofer97 is the reference RAFM steel developed for the requirements of the European fusion technology program. Its chemical composition has been designed and optimized to obtain good metallurgical properties comparable to the conventional Cr–Mo steels and reduced long term radioactivity.

The main aims of this paper are:

- investigate on possible structural materials for in-vessel components;
- describe mechanical properties of Eurofer97, with or without neutron irradiation, as principal candidate for in-vessel structural material;
- compare mechanical properties of Eurofer97 with other structural material (e.g. AISI 316).

2. Materials properties comparison

Structural materials for in-vessel components (like TBM and first wall) of future energy generating fusion reactors will be exposed to high neutron radiation and thermo-mechanical loads. Degradation of microstructure of structural materials under neutron irradiation as a result of displacement damage accumulation up to damage doses of 150 dpa and production of transmutation products, i.e. helium and hydrogen, will strongly influence materials' performance (4).

ITER materials activities were largely influenced by its time schedule. Advanced low activation materials such as vanadium alloys and SiC_f/SiC composites (SiC fibers in SiC matrix), and even martensitic steels were discarded in favour of the more robust stainless steel type 316L(N).

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 (4, 5, 6).

Vanadium alloys and SiC_f/ SiC composites developments marginalised due to several unresolved shortfalls (e.g. low temperature irradiation embrittlement and absence of reliable protective coating for vanadium alloys, and low thermal conductivity and low fracture toughness for SiC_f/SiC (6, 7)).

The reduced activation ferritic/martensitic (RAFM) steels and their oxide dispersion strengthened (ODS) variants are considered as primary candidate structural materials for in-vessel components with operating temperature range between 350 and 650 ◦C (4). This because metals and alloys with "body-centred cubic (Bcc)" crystal lattice structure, including iron and ferritic steels, show better resistance to prolonged irradiation than metals with "face-centred-cubic (Fcc)" lattices (8).

A comparison of the swelling under fission irradiation for ferritic steels against austenitic (fcc) steels is shown in fig. 1.

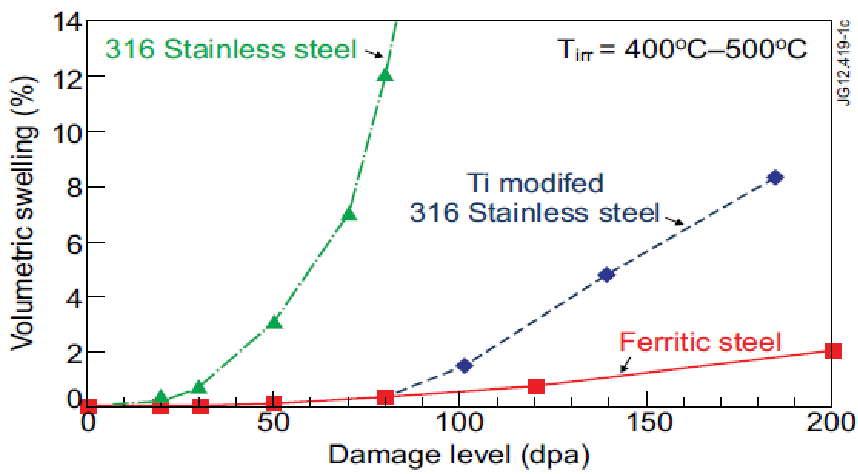

Fig. 1 Comparative swelling under fission neutron irradiation for ferritic and austenitic steels (8)

Some properties of ferritic/martensitic steel (F/M), V alloy and SiC_f/SiC (called simply SIC in the table) are compared in table 1 (9).

Fusion structural materials activities evolved achieving code qualified status (7).

	Units	F/M steel (~500 °C)	V4Cr4Ti (~600 °C)	SiC
Melting temperature	K	~1,800	2,170	
Density	kg/m^3	~7,900	6,050	2,500–3,200
Young's modulus	GPa	190 (Tavassoli)	120	200–300
Poisson's ratio	–	0.29–0.31	0.37	0.16–0.18
Thermal expansion coefficient	10^{-6} K^{-1}	11.5	10	3–4
Specific heat	J/kg K	630 (Tavassoli)	550	600
Thermal conductivity	W/(m K)	32.5 at 400 °C 33.0 @ 500 (Tavassoli)	36	5–20
Thermal stress figure of merit (Zinkle and Ghoniem 2000)	kW/m	~5.4 Fe–8–9Cr martensitic at 400 °C	~6.4 at 450–700 °C	2.0 at 800 °C
Maximum allowable combined stress	MPa	≈160	≈180	≈190
Maximum allowable burnup	%			≈3 %
Maximum temperature for compatibility with Li	°C	550–600	650–700	550
Maximum temperature for compatibility with PbLi	°C	450	650	800
Electrical resistivity	Ω m	0.07E−6	0.71E−6	0.002–0.05

Table 1 - Some properties of F/M, SIC and V4Cr4Ti (9)

3. Eurofer97

Fission experience has strongly influenced fusion program. 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.

In 1995 IEA defined a reference low activation steel to be produced in Japan and characterised by all members. The term RAFM (Reduced Activation Ferritic/Martensitic) steel was used.

Two industrial heats were fabricated and designated IEA-F82H heats, to distinguish them from an earlier F82H heat, also produced in Japan (6). These heats were characterised by all partners and the results were collected in dedicated relational database. In 1997, EU opted for a higher chromium and lower tungsten composition grade, Eurofer (also called Eurofer97) (6). Other countries are investigating similar compositions and targeting industrial productions for ITER TBMs. Table 2 presents chemical compositions of four RAFM steels produced in different countries along with the composition of the conventional Modified 9Cr–1Mo steel.

	Mod. 9Cr–1Mo	F82H	Eurofer	INRAFM	CLAM
Cr	8.5	7.7	9	9	9
C	1	0.09	0.11	0.11	0.1
Mn	0.4	0.16	0.4	0.5	0.45
P	<0.020	0.002	<0.005	<0.002	
S	<0.01	0.002	<0.005	<0.002	
V	0.21	0.16	0.2	0.22	0.2
B		0.0002	<0.001	<0.001	
N2	0.05	0.006	0.03	0.03	
O2		<0.01	<0.01	<0.01	
W		1.94	1.1	1.35	1.45
Ta		0.02	0.07	0.07	0.15
Ti		100 ppm	<0.01	<0.005	
Nb	0.08	1 ppm	<0.001	<0.001	
Mo	0.92	30 ppm	<0.005	<0.002	
Ni	<0.20	200 ppm	<0.0050	<0.005	
Cu	<0.10	100 ppm	<0.0050	<0.002	
Al	<0.040	30 ppm	<0.0010	0.005	
Si		1100 ppm	<0.050	<0.05	
Co		50 ppm	<0.0050	<0.005	
Sn		(<20 ppm)			
As		(<50 ppm)	As + Sn + Sb + Zr < 100 ppm	AS + Sn + Sb < 0.03	

Table 2 - Nominal chemical compositions of RAFM steels (6).

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) (6). 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 (6).

Their main advantages over austenitic stainless steels are related to the excellent dimensional stability (creep and swelling) under neutron irradiation (7). In addition, they present lower coefficients of thermal expansion and higher coefficients of thermal conductivity at high temperatures (6). Development of RAFM steels has been the object of extensive cooperation between the different fusion parties; Eurofer97 is one of the variants developed in the European Union within the framework of the EFDA.

Table 3 reports the minimum ductility requirements of the materials as defined by ESPN/RCC-Mx and that of Eurofe97 in irradiated/un-irradiated conditions.

	ESPN/RCC-MX Limit	Eurofer97 at BOL	Eurofer97 at 3 dpa
ε_t (RT)	>14%	22%	~14% (300 °C)
Toughness (0 °C)	>40 J	220 J	~200 J (300 °C) ~23 J (RT)
S_y/S_u (RT)	<0.85	0.83	0.92 (300 °C)

Table 3 - Minimum ductility requirements of the materials as defined by ESPN/RCC-MX and that of Eurofer in irradiated/un-irradiated conditions (7).

Eurofer achieved code qualification status after several years in 2013 with its entry in RCC-MRx edition 2012 (under Section III, Tome 1, Sub-Section Z and denomination A3.19AS) (6). F82H is expected to follow with its entry in the Japanese Code.

3.1 Eurofer mechanical properties (un-irradiated)

3.1.1 Tensile strength and ductility

Eurofer97 shows excellent mechanical properties in the unirradiated condition from −80 up to 550 °C. Above this temperature range the structural application of the steel is limited mainly by considerable loss of tensile and creep strengths (4).

The yield strength (Sy) and ultimate tensile strength (Su) of Eurofer97 with temperature compared to those of the 316L(N)-IG steel are reported in fig. 2. In the whole range of temperatures relevant for TBM operation (300-550 °C), Eurofer97 exhibits a much lower strain hardening capability compared to 316L(N)-IG. The lack of strain-hardening capability is also evident in Fig. 3 which compares the uniform (ε_u) and total elongation at rupture (ε_t) for Eurofer97 and 316L(N)-IG. The reduced ductility/strain-hardening capability of Eurofer97 respect to 316L(N)-IG is shown in Fig. 4 which reports stress–strain curves for the two steels at 500 °C.

According to the values Eurofer97 could be considered as a semi-brittle or even brittle material even in the absence of irradiation damage (7).

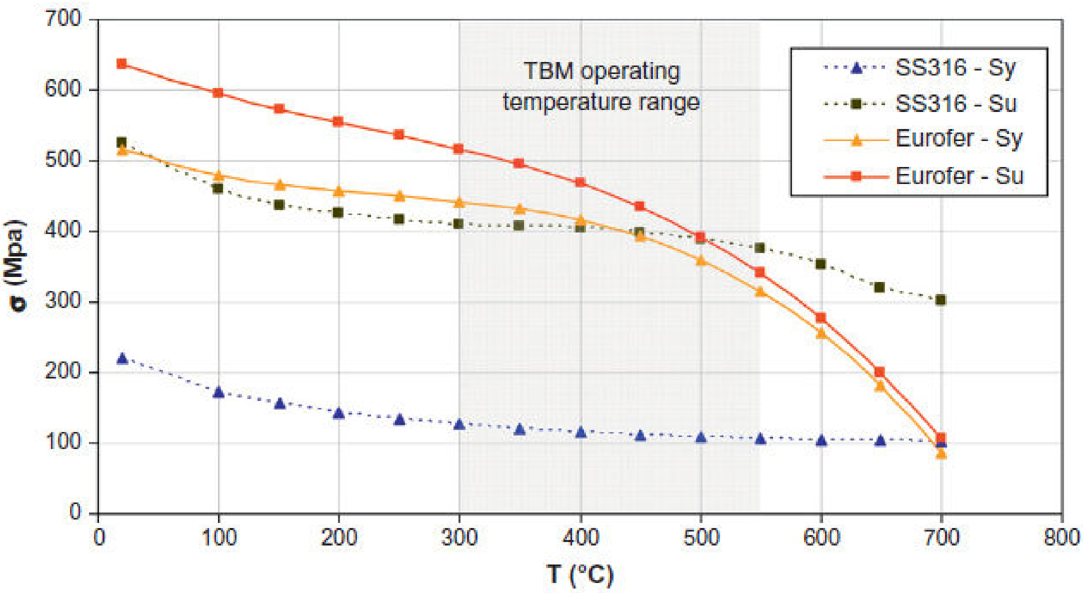

Fig 2 - Eurofer97 and 316L(N)-IG yield strength (Sy) and ultimate tensile strength (Su) (7)

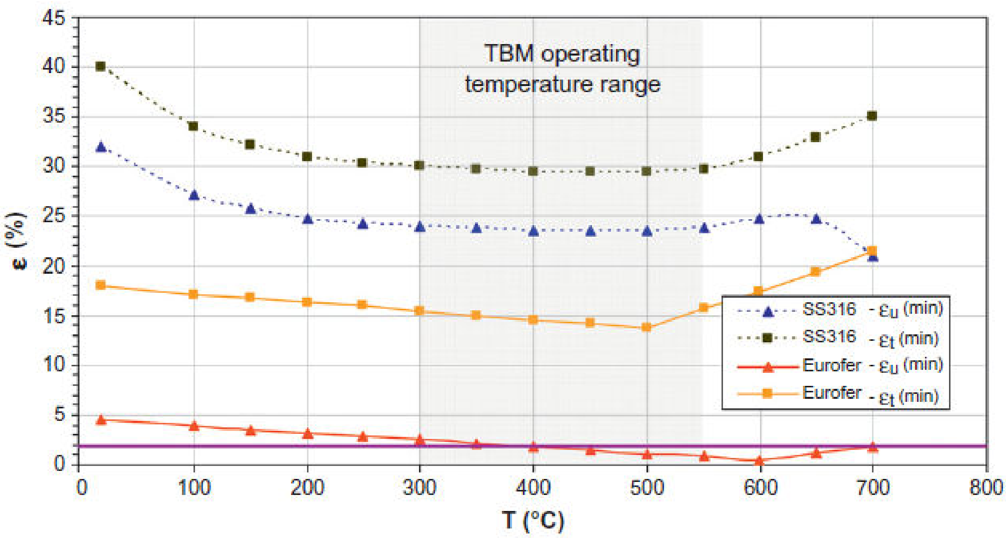

Fig. 3- Uniform elongation (ε_u) and total elongation (ε_t) values for Eurofer97 and 316L(N)-IG (7).

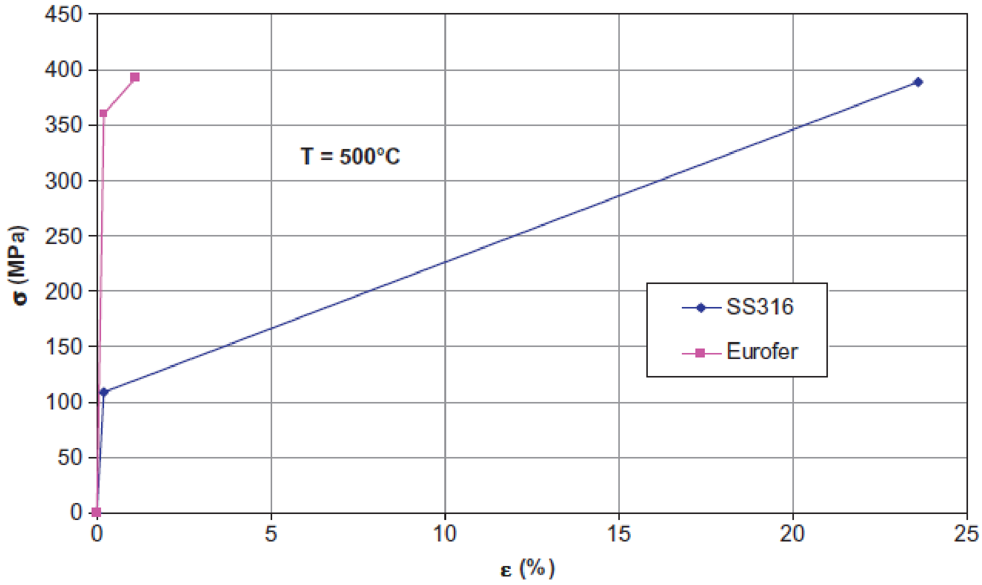

Fig. 4 - Schematized stress-strain curve for Eurofer97 and 316(N)-IG at 500 °C (7)

3.1.2 Thermal creep

The creep behaviour of Eurofer97 is well characterised. Eurofer97 shows adequate creep rupture strength, comparable to that of other RAFM steels. Values of allowable stress S_t for Eurofer97 are shown in Fig. 5.

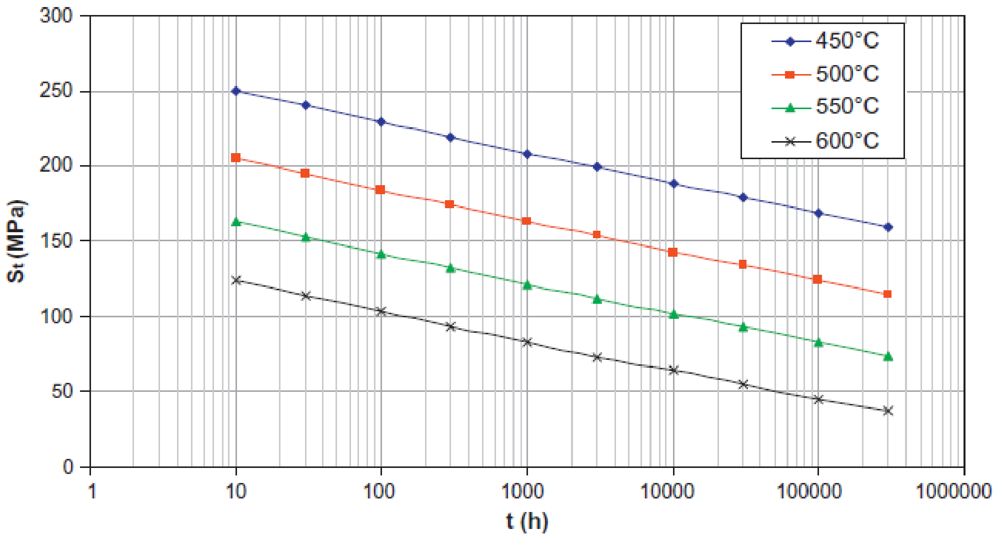

Fig. 5 – Eurofer allowable stress S_t values (7)

3.1.3 Fatigue proprieties

Eurofer97 has very pronounced softening under Low cycle Fatigue (LCF) tests: the cyclic stress amplitude decreases rapidly after a few cycles and then stabilizes at a value which decreases slowly as a function of the number of cycles, dropping sharply just before failure of the specimen. During fatigue tests, when saturation is reached, the range of the stable stress $\Delta\sigma$ can be plotted as a function of the imposed strain range $\Delta\varepsilon$.

The curve thus determined is called the cyclic stress–strain curve. Cyclic stability is not achieved in LCF tests of Eurofer97: in this case, the cyclic stress–strain curves corresponding to half-lives are reported as cyclic stress–strain curves. Fig 6 reports the cyclic stress-strain curves compared with monotonic stress-strain curves (7).

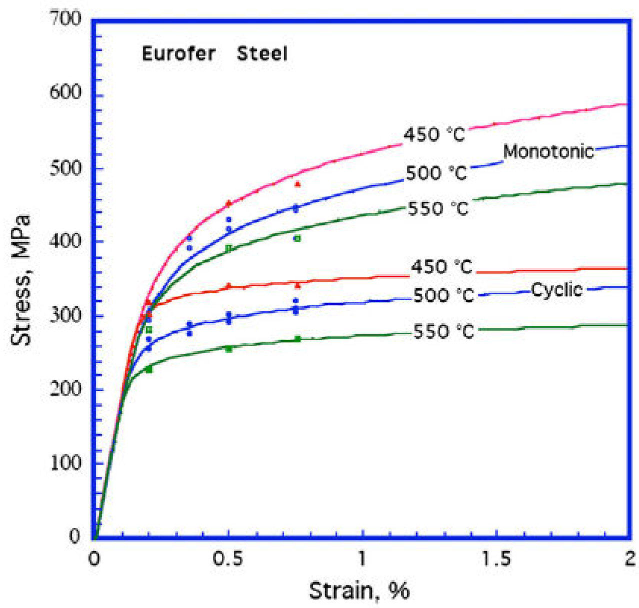

Fig. 6 - Reduced cyclic stress-strain curves for Eurofer97 at different temperatures (7)

3.1.4 Creep-fatigue interaction

In vessel components like TBM or Divertor components will operate under cyclic, non-symmetrical thermo-mechanical loadings that can lead to creep damage accumulation. These operating conditions can be simulated by introducing a hold time in LCF tests. The fatigue behaviour of

Eurofer97 becomes much more complicated when introducing hold times in LCF (Low Cycle Fatigue) tests, showing very different characteristics with tension, compression or symmetrical hold times (7). Fig. 7 reports the influence of hold times on the fatigue life of Eurofer97.

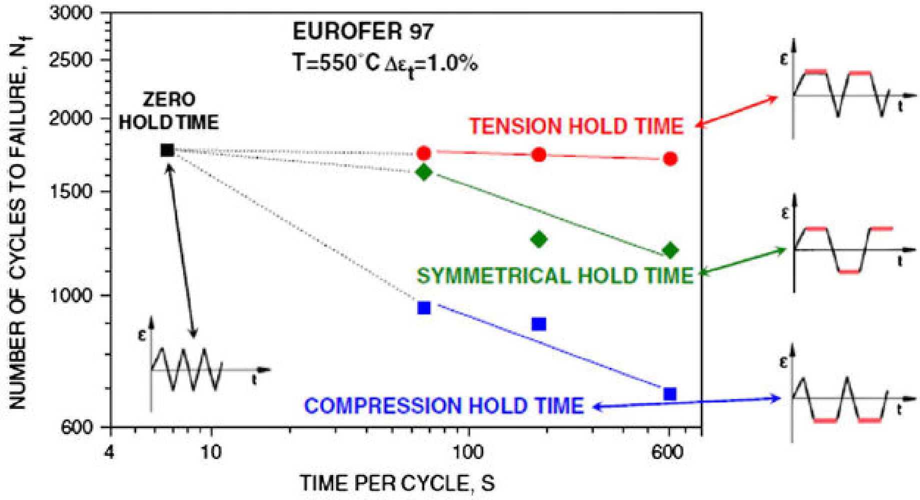

Fig. 7 - Influence of hold time on the fatigue life of Eurofer97 (7)

3.2 Neutron irradiation effects on Eurofer97 and other RAFM steels

3.2.1 Tensile properties

Fig. 8 shows Yield Stress (R_{p02}) vs. test temperature (T_{test}) for EUROFER97 in the unirradiated condition and after neutron irradiation in different medium and high dose European irradiation programmes at target irradiation temperatures (T_{irr}) between 300 and 350 °C (4).

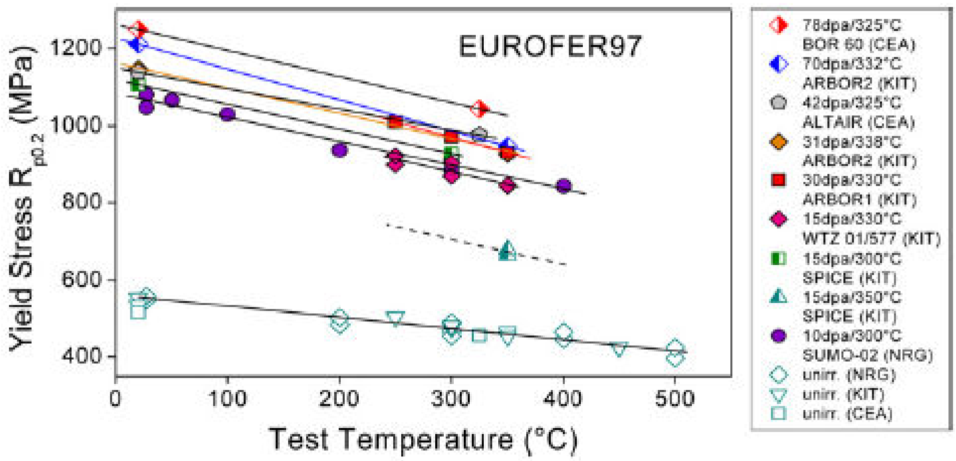

Fig. 8 - Yield stress vs. Temperature for Eurofer97 in the unirradiated condition and after neutrons irradiations in different irradiation programme (4, 10).

Neutron irradiation leads to substantial increases in the Yield Stress which is sensitive to the irradiation parameters, i.e. irradiation dose and temperature. Furthermore, for given irradiation conditions the Yield Stress increase depends on the test temperature and is larger at low test temperatures.
The test temperature and dose dependences of the Ultimate Tensile Strength (Rm) resembles to that of the Yield Stress. Close values of the Ultimate Tensile Strength (Rm) and Yield Stress (Rp0.2) in the irradiated conditions indicate a strong suppression of the strain hardening capability under neutron irradiation.

The evolution of the hardening, as the increase in Yield Stress, with damage dose for different product forms of EUROFER97 and for other selected RAFM steels for Tirr = 300–335 °C and Ttest = 300–350 °C is summarized in Fig. 9.

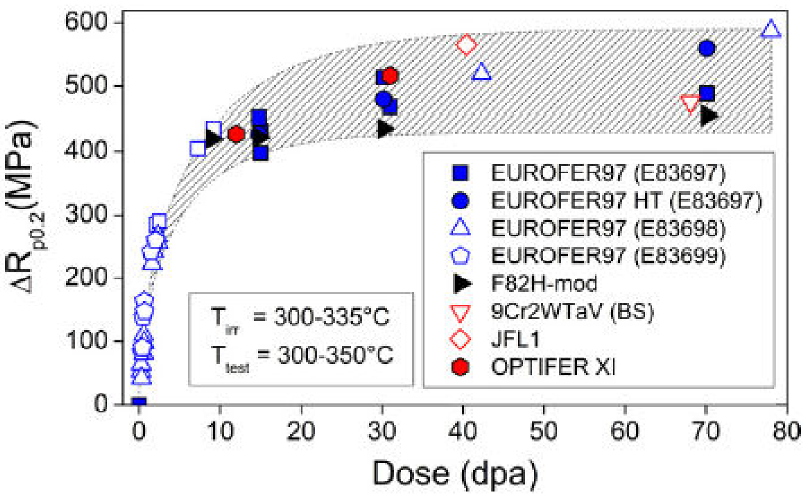

Fig. 9 Irradiation hardening vs. Irradiation dose for eurofer97 and other RAFM steel for Tirr= 300-335 °C and Ttest= 300-350 °C.

Neutron irradiation leads to a substantial increase in the Yield Stress of RAFM steels with the damage dose. The Yield Stress increase is rather steep at doses below 10 dpa. The hardening rate appears to be significantly decreased at the achieved damage doses and a clear tendency towards saturation is identified.
For the analysis of high dose irradiation behaviour of EUROFER97 differentiation has to be done between different product forms as well as different heat treatment conditions. In fact there is a

strong sensitivity of materials' mechanical properties and irradiation performance to metallurgical parameters.

The hatched area marks the scattering band of high dose hardening for different RAFM steels.
It is important to note that to the reasons for the data scattering belong not only the differences in the metallurgical variables, but also variations and uncertainties in the irradiation conditions.

Fig. 10 shows Uniform Strain and Fracture Strain of selected RAFM steel specimens irradiated to 70.1 dpa at 331.5 °C and tested at 350 and 20 °C. Rather low values of the Uniform Strains below 1% are observed for all investigated RAFM steels. The Fracture Strains, in contrast, remain at a high level above 9–10%.

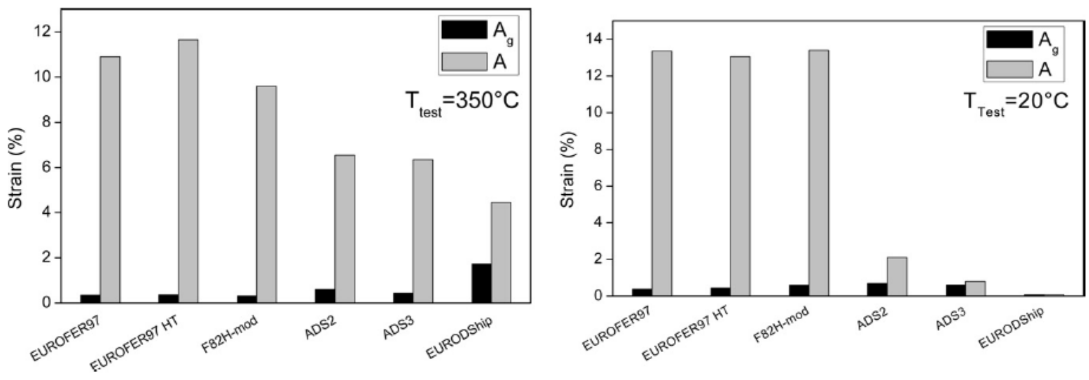

Fig. 10 - Uniform strain (Ag) and fracture strain (A) of 70.1 dpa, 331.5 °C irradiated RAFM materials tested at 350°C (left) and 20 °C (right).

The boron doped Steels ADS2 and ADS3 (to study the effect of helium generation) show larger Uniform and reduced Fracture Strains in comparison to base RAFM steels.

The evolution of Strain with irradiation dose for different product forms of EUROFER97 for irradiation temperatures between 300 and 335 °C and test temperatures between 300 and 350 °C is shown in Fig. 11. The both tensile properties show a strong reduction from their values in the reference unirradiated state already at a damage dose of 2.1 dpa. The Uniform Strain (Ag) is scattered mostly below 0.5% in the irradiated state. Though strongly reduced, the Fracture Strain (A) remains mostly at or above 10% for irradiated specimens.

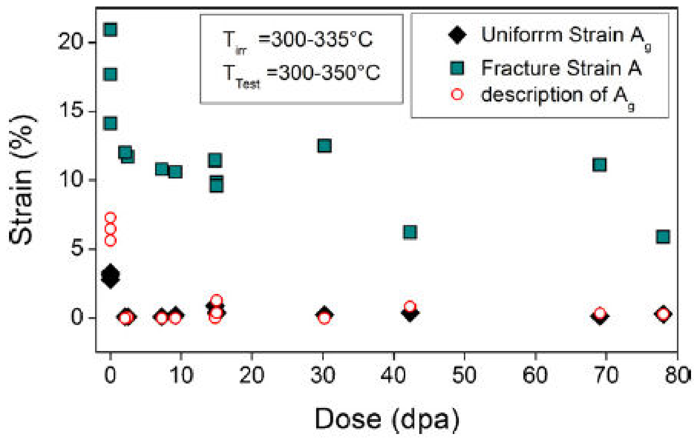

Fig. 11 Uniform and fracture strain vs Damage dose for different product forms of Eurofer97 (4, 10)

3.2.2 Impact properties

The role of irradiation temperature on the impact properties of EUROFER97 and other RAFM steels was studied in SPICE program.

Fig. 12 shows the DBTT (**D**uctile–**B**rittle **T**ransition **T**emperature. A material cooled below the DBTT has a much greater tendency to shatter on impact instead of bending or deforming) vs. irradiation temperature for EUROFER97 and other RAFM steels from SPICE irradiation programme.

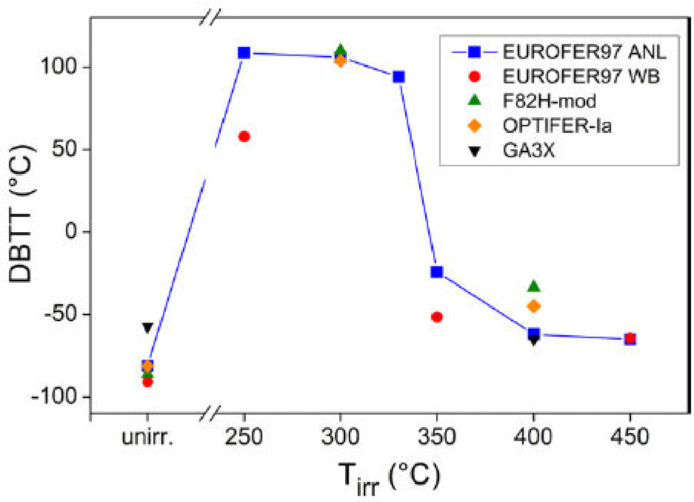

Fig. 12 - Change in DBTT as a function of irradiation temperature for various Eurofer alloys at 16 dpa exposure (4, 10)

The DBTT of all steels is influenced most at low irradiation temperatures (Tirr ≤ 330 °C). The DBTTs of the materials irradiated at or above 350 °C remain below −24 °C and, hence, are well below the material application temperature. On the basis of this diagram a temperature window between 350 and 550 °C is proposed for operation of the FW, Divertor and Blanket components.

Fig. 13 shows the evolution of the neutron irradiation induced embrittlement (measured in impact tests) with dose for EUROFER97 and F82H steels at irradiation temperatures between 300 and 337 °C (4, 10).

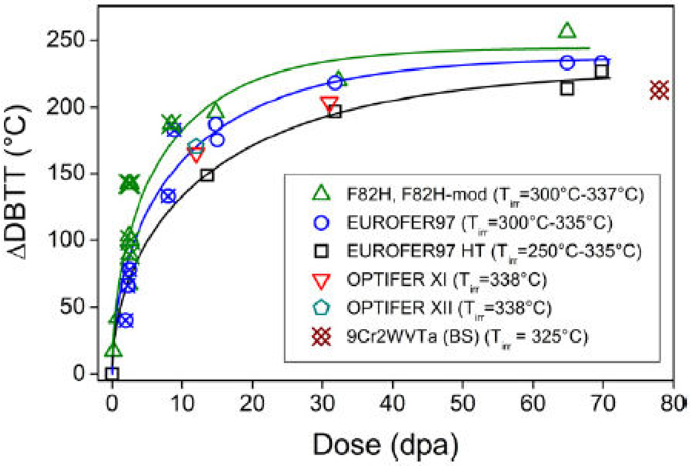

Fig. 13 - Irradiation shifts of the DBTT vs. Dose for eurofer97 and other RAFM steels.

In case of EUROFER97, differentiation is made between specimens machined from as-delivered products and specimens machined from the plates subjected to pre-irradiation heat treatment (HT). The results on F82H and F82H-mod are plotted together for different heat treatments and material compositions. The pre-irradiation heat treatment (HT) of Eurofer97 leads to considerable improvement of the irradiation resistance at doses up to 30 dpa. At the achieved damage doses, however, the embrittlement of Eurofer97 HT becomes comparable to that of Eufofer97. All RAFM steels show steep increase in the ΔDBTT with dose below 15 dpa. With farther increasing the damage dose the embrittlement rate decreases and a clear tendency towards saturation is observed at the achieved damage doses.

3.2.3 Helium effects

The helium effects are studied in different simulation experiments including fission reactor irradiation of boron doped steels, irradiation under spallation target environment, multi-ion beam-irradiation, etc.

Helium effects are not sufficiently understood due to absence of an irradiation facility with fusion reactor relevant neutron spectrum and have to be a subject of future investigations. Different simulating techniques used, e.g. fission reactor irradiation of boron doped model steels or spallation neutron and proton irradiation of RAFM steels most probably strongly overestimate helium effects. Moreover, helium effects will strongly depend on the irradiation temperature. Boron doping technique yielded progressive embrittlement with increasing helium concentration (10–430 appm) at Tirr ≤ 350 °C; the embrittlement rate was however reduced at achieved helium contents. Helium embrittlement was considerably reduced at Tirr = 450 °C. Synergistic helium and dpa effects under spallation target environment at Tirr ≤ 380 °C yielded linear increase of DBTT shift with produced helium up to 1600 appm.

3.2.4 Swelling

The swelling of RAFM steels is sensitive to irradiation or implantation temperature, helium and dpa production rates and steel virgin microstructure. The neutron irradiation of boron and nickel doped RAFM steel at 300 °C yielded nearly no swelling while irradiation at 400 °C, however, 1.2% and 1.1% volumetric swelling was observed.
The absence of irradiation facility with fusion relevant neutron spectrum does not allow the assessment of swelling under in-service condition as there still remain uncertainty in the helium content and irradiation temperature for the onset of pronounced swelling for fusion relevant dpa and helium production rates.

3.2.5 Irradiation effects of on fatigue

Few data are available on the consequences of neutron irradiation on the fatigue behaviour of Eurofer97 and other RAFM steels. As a general rule, the fatigue lifetime of the irradiated material should be shorter because of loss of ductility and significant increase in cyclic softening (7).

3.2.6 Application of Eurofer under PWR conditions

Eurofer97 can also be considered to be used in water cooled breeding blanket under pressurized water reactor (PWR) condition with coolant inlet/outlet temperatures of 275/325 °C (at a pressure of ~15.5 MPa) taking into account that neutron irradiation of this steel in the temperature range between 275 and 325 °C results strong degradation of the mechanical properties (30). In fact the DBTT will be raised above room temperature already after few dpa and at 70 dpa at 330 °C the value of DBTT is at around 152 °C.

Helium effects are expected to lead to further degradation of DBTT.

From first experiments the swelling seems not to be a problem under PWR condition.

Application of ERUOFER97 under PWR condition will be problematic because the irradiation induced embrittlement must be considered at least for normal and abnormal reactor shut downs particularly where the temperature goes below the DBTT of the irradiated material. Recovery heat treatments prior to reactor cool down can be utilized to avoid handling of brittle components which however might be a challenge with regard to needed homogeneous heating. Under such circumstances implementation of the recovery heat treatments (550°C/3 h) will be required in order not to allow the DBTT to come close to a coolant inlet temperature of 275 °C.

Furthermore, corrosion behaviour of EUROFER97 under PWR condition is considered as another concern. Stress corrosion cracking (SCC) phenomena need to be investigated in dedicated experiments under unirradiated and irradiated conditions.

3.2.7 Databases

Distinction is to be made between material's properties data and code-qualified materials properties data (6). In the case of code-qualified properties, all data collected must be harmonised and validated before they are entered in the databases. 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. For the ITER Interim Structural Design Analyses

(ISDC) only the code-qualified part of the data was used (6). SDC-IC harmonised ITER MPH containing mostly code-qualified data.
All Eurofer data entered in the EU databases are now code qualified. Extracts from these databases are used at first to derive design allowable for ITER Test Blanket Modules (TBMs), since TBM design (not requiring irradiation data higher than 3 dpa) is in an advanced stage.
For DEMO, where doses are much higher, design is still evolving and effects of irradiation damage are more complicated. Furthermore, some experimental data generated and analysed are still for understanding the irradiation damage, particularly the effects of higher helium formation under 14 MeV neutrons and its synergistic effects when combined with dpa.
Presently the EU RAFM database has suited data concerning Eurofer steel.

3.3 ODS Eurofer

Advanced Oxide Dispersion Strengthened(ODS) EUROFER steels with 0.3 wt.% Y_2O_3 exhibit good mechanical properties in the unirradiated state in the temperature range from -50 to 650 °C . Yield and tensile strength are about 35% higher than for EUROFER97 up to 700 °C. The impact properties are somewhat worse than that of EUROFER97 but still in an acceptable range. Low temperature neutron irradiation (Tirr ≤340 °C) leads to strong embrittlement of ODS EUROFER steels.
Irradiation at 450 and 550 °C of recently developed ODS EUROFER steel yielded nearly no changes of the mechanical properties . Having in mind a strong recovery of the radiation damage in base EUROFER97 steel above 350 °C, the operation temperature window between 350-400 and 650 °C can be proposed for ODS EUROFER (9%Cr) steel. The influence of helium on the mechanical properties of ODS EUROFER is not available yet and a dedicated study is required in the future (4).

3.4 Summary on neutron irradiation effects on Eurofer and other RAFM steel

Following are summarised key issues related to neutron irradiation on TBM and divertor made on Eurofer (4, 10).
1. As reported by several sources (4, 7, 10), 335 °C is the most critical irradiation temperature in terms of hardening and loss of ductility for RAFM steels. In fact low temperature neutron

irradiation ($T_{irr} \leq 335$ °C) leads to strong hardening and embrittlement of Eurofer97. Minor hardening and embrittlement observed at Tirr = 350 °C indicates considerable healing of radiation damage. Neutron irradiation at Tirr ≥ 400 °C has nearly no impact on the mechanical properties.

2. The increase of the Yield Stress of RAFM steels is rather steep at doses below 10 dpa at Tirr ≤ 335 °C. In spite of large scattering of low temperature, high dose hardening data a clear reduction of the hardening per dose increment is observed at achieved damage doses of 70–80 dpa. Eurofer shows saturation of hardening at 70 dpa. Ductility properties (Uniform Strain, Total Strain) seem to saturate already above 2.5 dpa.

3. All RAFM steels show steep increase in the ΔDBTT with dose below 15 dpa at Tirr ≤ 335 °C. At 70 dpa Eurofer97 indicates saturation behaviour of low temperature embrittlement.

4. Post irradiation annealing at 550 °C for 3 h leads to a nearly complete recovery of the impact and tensile properties of low temperature (Tirr = 335 °C) irradiated Eurofer97 indicating substantial healing of radiation defects. In fusion reactor this heat treatment has to be done by He. This knowledge leads to the following proposed life cycle operation: six month operation followed by few hours annealing at 550 °C with He. During this annealing the impact properties strongly recover. Afterwards four month operation followed by few hours annealing at 550 °C with He. And finally one month of operation, than replacement (5).
Helium effects cannot be healed out by post irradiation annealing.

5. Helium effects are not sufficiently understood due to absence of an irradiation facility with fusion reactor relevant neutron spectrum and have to be a subject of future investigations. Different simulating techniques used, e.g. fission reactor irradiation of boron doped model steels or spallation neutron and proton irradiation of RAFM steels most probably strongly overestimate helium effects. Moreover, helium effects will strongly depend on the irradiation temperature. Boron doping technique yielded progressive embrittlement with increasing helium concentration (10–430 appm) at Tirr ≤ 350 °C, the embrittlement rate was however reduced at achieved helium contents. Helium embrittlement was considerably reduced at Tirr = 450 °C. Synergistic helium and dpa effects under spallation target environment at Tirr ≤ 380 °C yielded linear increase of DBTT shift with produced helium up to 1600 appm.

6. The RAFM steels are highly suited for the special fusion reactor design with the operating temperature range between 350 and 550 °C for the FW and BB. In the irradiation temperature range between 350 and 550 °C the application of Eurofer97 will be further limited by helium effects. Helium effects are not sufficiently understood due to absence of an irradiation facility with fusion spectrum. By considering DEMO relevant helium to dpa ratio of 10 appm/dpa helium effects will be tolerable up to a damage dose of 40 dpa and up to helium contents of 400 appm He in the temperature window between 350 and 550 °C. The mechanical performance of RAFM steel at low irradiation temperatures (Tirr < 350 °C) will be mainly limited by dpa induced embrittlement. By utilizing post irradiation annealing of FW and BB structures for the recovery of dpa effects at low irradiation temperatures the helium effects will be tolerable up to a damage dose of at least 40 dpa

7. Irradiation behaviour with respect to impact properties is rather poor for early developed ODS Eurofer steels.

4. Improved structural materials for fission and fusion energy

Existing structural materials have rather limited operating temperature regimes where they can be utilized in a neutron irradiation environment as summarized in Fig. 14 for moderate damage levels of 10 to 50 dpa.

At low temperatures, the reduced ductility associated with low temperature radiation hardening creates conditions where modified (larger safety margin) engineering design rules must be used. In cases where fracture toughness [1] is reduced by low temperature irradiation, the operating temperature is restricted to higher temperatures where embrittlement does not occur. The upper operating temperature limit is typically determined by thermal creep strength or high temperature helium embrittlement considerations.

[1] A quantitative way of expressing a material's resistance to brittle fracture when a crack is present, a material with high fracture toughness is more prone to ductile fracture. Brittle fracture is characteristic of materials with less fracture toughness

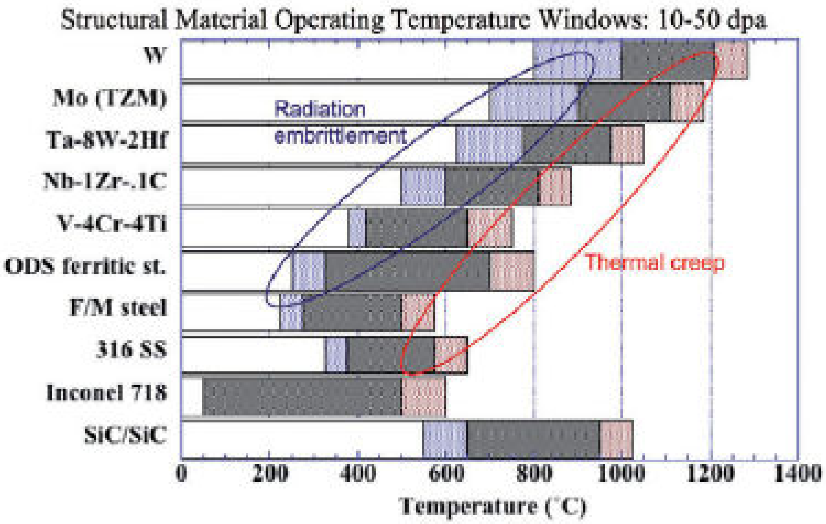

Fig. 14 - Estimated operating temperature windows for structural materials in nuclear energy systems for damage levels of 10 to 50 dpa (11).

The "Fourth Generation Ferritic-Martensitic steels" (that are FM steel with Thermo-Mechanical Treatment (TMT) to improve the microstructure) have been developed with a focus on improving strength compared to the Eurofer generation steel and creep resistance at high temperature (up to ~ 650 °C) (fig 15).

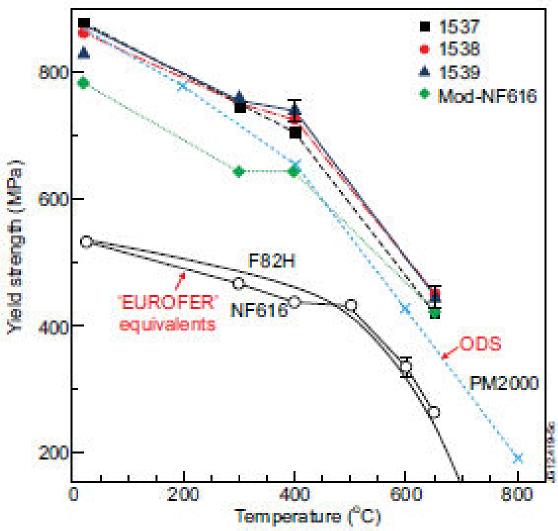

Fig. 15 - Yield stress of US Generation IV HT FM steels (8).

The microstructure produced in these latest generation steel are expected to provide improved radiation resistance over a broad range of temperatures due to higher precipitate densities and other radiation defect sinks, which have the potential to improve the low temperature embrittlement issue. These steels are just entered fission irradiation testing in the US. More testing is needed, but it has been clearly demonstrated that substantial improvement in multiple mechanical properties before irradiation, including thermal creep strength, fracture toughness (DBTT and upper shelf toughness), etc., can be achieved compared to 1980-1990 grades steel.

Development of structural materials for large-scale energy application is historically a long and costly process, due to the extended period to develop a new alloy followed by an even longer proof testing period to validate the performance of the material in prototypic environments for appropriate licensing authorities.

5.Conclusions

A brief overview on fusion structural materials such as SiC_f/SiC composites (SiC fibers in SiC matrix), Vanadium alloy and mainly "Reduced activation ferritic/martensitic steels" (RAFM) (and particularly Eurofer97) has been done. In particular we found that RAFM steel is the primary choice material for Test Blanket Modules structural application for ITER and in future fusion power plants with operating temperature range between 350 and 550 °C.

These steels have been developed in order to simplify special waste storage of highly radioactive structures of fusion reactor after service. Eurofer 97 is the reference RAFM steel developed for the requirements of the European fusion technology program. The reasons for selection of RAFM steels are:

- good overall balance of mechanical properties (strength ductility, fracture toughness, creep resistance, fatigue resistance);
- the properties can be adjusted and to some extent tailored (e.g. by chemical composition but even more from heat treatments);
- there is broad industrial experience with FM steels in nuclear and non-nuclear facilities;
- they have superior properties to austenitic steels:
    - in terms of thermo-physical properties and thermal stress factor (factor 1.7 to 2 compared to AISI 316);

- in terms of neutron irradiation stability of bcc steels (swelling is very low compared to AISI 316);
- there is either no or much reduced “high-temperature” embrittlement.

The main issues with Eurofer are:

-low temperature radiation embrittlement. Post irradiation tests, after fission irradiation, show large hardening and ~ 200 °C increase in the ductile to brittle transition temperature (DBTT) occurs for irradiation temperature of ~ 300-350 °C after ~ 20 dpa. This raises serious concerns about the viability of these steels for fusion structure operating at or below 300-350 °C without mitigation measures, particularly since potential additional embrittlement from the effects of neutrons with fusion relevant energy levels have not been included in the results. Helium content, which will be produced with fusion neutrons, may cause additional matrix hardening and may migrate to grain boundaries and increase the tendency to fracture;
-loss of uniform elongation and swelling under irradiation;
-water corrosion and irradiation assisted cracking;
-degradation of mechanical properties in weld heat-affected-zones (HAZ) under irradiation;
-fatigue and creep-fatigue cause “cyclic softening”.

In addition to this, since most of irradiation data up to 80 dpa for Eurofer have been obtained in fission reactors and do not cover higher He/dpa found under fusion spectra, Eurofer qualification at higher doses, above 20 dpa, is not achieved.

A short introduction has been done to the “Fourth Generation Ferritic-Martensitic steels” (that are FM steel with thermo-mechanical treatment (TMT) to improve the microstructure). These steels are just entered fission irradiation testing in the US. More testing is needed, but it has been clearly demonstrated that substantial improvement in multiple mechanical properties before irradiation, including thermal creep strength, fracture toughness (DBTT), etc., can be achieved compared to 1980-1990 grades steel.
Development of structural materials is historically a long and costly process, followed by an even longer proof testing period.

Annex 1. "Eurofer pecularieties"

Reduced Activation Ferritic Martensitic (RAFM) steel is the primary choice material for Test Blanket Modules structural application for ITER and in future fusion power plants (8). These steels have been developed in order to simplify special waste storage of highly radioactive structures of fusion reactor after service (8). With this objective some alloying elements such as Mo, Nb and Ni, present in the commercial martensitic steels, have been replaced by other elements which exhibit faster decay of induced radioactivity such as Ta, W and V.

The reasons for selection of RAFM steels are:

- good overall balance of mechanical properties (strength ductility, fracture toughness, creep resistance, fatigue resistance);
- the properties can be adjusted and to some extent tailored (eg by chemical composition but even more from heat treatments);
- there is broad industrial experience with FM steels in nuclear and non-nuclear facilities (as compared to other materials like Vanadium alloys);
- -they have superior properties to austenitic steels:
    - in terms of thermo-phisical properties and thermal stress factor (factor 1.7 to 2 compared to SS316);
    - in terms of n-irradiation stability of bcc steels (swelling is very low compared to Stainless Steel);
    - there is either no or much reduced "high-temperature" embrittlement.

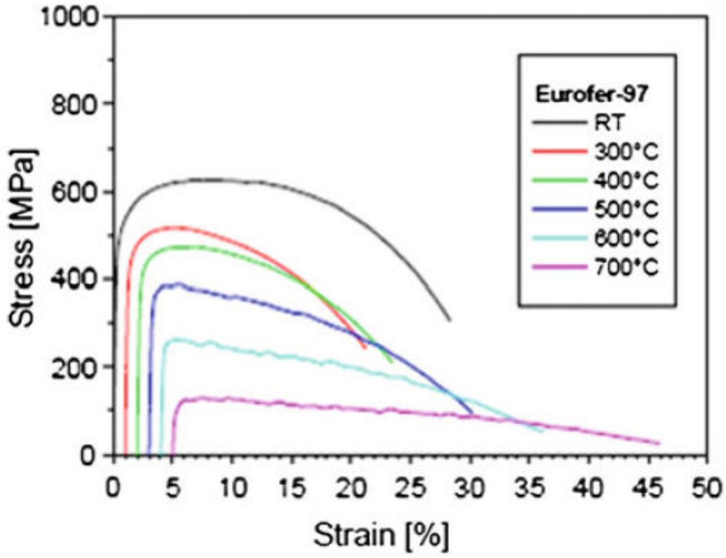

Fig. A1.1 – Stress versus strain of Eurofer at various temperature (9)

The main issues with Eurofer are:

-low temperature radiation embrittlement. Eurofer embrittles fairly rapidly under fission irradiation. This occurs at temperature about 325-350 °C and He content which will be produced with fusion neutrons is expected to make this worse, since Helium may cause additional matrix hardening and may migrate to grain boundaries and increase the tendency to fracture;

-loss of uniform elongation and swelling under irradiation;
-water corrosion and irradiation assisted cracking;
-degradation of mechanical properties in weld heat-affected-zones (HAZ) under irradiation;
-fatigue and creep-fatigue cause "cyclic softening".

In addition to these technical issues there is a lack of materials database for 14 MeV neutron irradiation effects and this impedes meaningful design code development. Another issue is the lack of design rules for high-temperature creep-fatigue.

The irradiation damage which causes the embrittlement and hardening is known to be 'annealed' if irradiation occurs at higher temperatures (above 300-350 °C). It is due to the thermally-induced dissolution of small defect aggregates as the temperature (and hence energy) is increased. Post irradiation tests, on steel after fission irradiation, show large hardening and an ~ 200 °C increase in the ductile to brittle transition temperature (DBTT) occurs for irradiation temperature of ~ 300-350 °C after ~ 20 dpa. This raises serious concerns about the viability of these steels for fusion structure operating at or below 300-350 °C without mitigation measures, particularly since potential additional embrittlement from the effects of neutrons with fusion relevant energy levels have not been included in the results.

The AISI 316 steel has a limited power exhaust capability and limited resistance to radiation effects.

The ductility and fracture toughness of 316 steel are severely degraded during irradiation around 300 °C and doses of ~ 10 dpa. At intermediate temperature of 400-600 °C they are susceptible to significant volumetric void swelling for doses >20 dpa, depending on the irradiation spectrum and other experimental variables.

AISi 316 steels have been shown to suffer from severe He-embrittlement at high temperature (>550 °C).

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