Journal of Nuclear Materials 386–388 (2009) 254–256

Contents lists available at ScienceDirect

Journal of Nuclear Materials

journal homepage: www.elsevier.com/locate/jnucmat

Overview of the tensile properties of EUROFER in the unirradiated and irradiated conditions

Enrico Lucon *, Willy Vandermeulen

SCK•CEN, Institute for Nuclear Material Science, Mol, Belgium

ABSTRACT

On the basis of the results accumulated since the late 90s, several European institutions have recently initiated activities aimed at providing an overview and critical assessment of the mechanical and microstructural properties of EUROFER, the reduced activation ferritic/martensitic steel that is the European candidate structural material for a future fusion reactor. SCK•CEN has been in charge of collecting and analyzing tensile data; the results of our assessment will be presented in this paper, where tensile data have been investigated in relation with various irradiation parameters. Comparisons are also provided with similar data for other RAFM steels, including the Japanese reference RAFM steel F82H-mod.

1. Introduction

Reduced activation ferritic/martensitic (RAFM) steels are presently considered as primary structural materials for a demonstration fusion plant (DEMO). Although service conditions are not yet fully established in terms of temperatures, stresses or environment, simplified studies are available investigating different concepts [1]. Predictably, irradiation effects are of highest concern amongst environmental conditions in a fusion reactor.

The European Union reference material is a 9Cr–1.1W–0.2V–0.07Ta–0.1C RAFM steel, denominated EUROFER (or EUROFER97), which exhibits a tempered martensitic microstructure and presently allows operation up to 550 °C [2,3]. Since one of the main issues of RAFM steels is the effect of irradiation at temperatures lower than about 400 °C, the European Fusion Development Agreement (EFDA) has devoted considerable efforts and budget to the characterization of post-irradiation mechanical and microstructural properties of EUROFER. Irradiations have been conducted in test reactors up to a wide range of radiation damage: from 0.3 up to 70–80 dpa [4]. In 2005, EFDA launched an activity aimed at the collection and critical assessment of the mechanical and microstructural property data of irradiated EUROFER, including also properties in the unirradiated condition and comparisons with other RAFM steels, such as F82H, JLF-1, CLAM and others.

This paper presents an overview of the tensile property data of EUROFER in the unirradiated and irradiated conditions, conducted by SCK•CEN within the above mentioned activity [5].

* Corresponding author.
E-mail address: elucon@SCKCEN.BE (E. Lucon).

0022-3115/$ - see front matter © 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.jnucmat.2008.12.109

2. Database of RAFM steels tensile properties

The first phase of the activity consisted in the collection of available tensile test results for EUROFER in the unirradiated and irradiated conditions, using all available sources, including 'informal' contacts with investigators in the case of yet unpublished data.

An EXCEL97 database was compiled in order to facilitate the analysis of the available information. The database contains more than 1000 records, each record corresponding to the results of an individual tensile test. It includes data for EUROFER, F82H, JLF-1, CLAM and OPTIFER, as well as for other experimental 9Cr and 12Cr alloys; these latter have not been used for the analyses presented here. For every record in the database, the following information is provided (when available): test and material identification, heat treatment, irradiation conditions, specimen dimensions, test conditions and test results (yield and tensile strength, uniform and total elongation, reduction of area).

3. Strategy used and materials considered

In the unirradiated condition, EUROFER tensile properties have been analyzed as a function of test temperature (T_{test}) and compared to equivalent information for other relevant RAFM steels (F82H, JLF-1, CLAM and OPTIFER).

As far as irradiated properties are concerned, the collected information allows tensile results to be analyzed as a function of irradiation temperature (T_{irr}) and accumulated dose (dpa). Data pooling was necessary in order to detect and investigate the influence of each experimental variable. Pooling was performed by grouping available data in terms of T_{irr}, dpa and T_{test}; for the former two variables, 'data bins' were created by considering data within a reasonably narrow range, where the effect of T_{irr} or dpa variation could be deemed negligible.

More limited investigations, due to the scarcity of relevant information, were also performed in terms of dose rate and irradiation environment, using data generated from experiments performed in HFR (Petten) and BR2 (Mol).

The chemical compositions of the RAFM steels considered in this study and the relevant heat treatment information are provided in the open SCK•CEN report [5], along with all relevant details of the investigations performed. For EUROFER, two batches were considered: the original batch of 3.5 tons (EUROFER-1) produced in 1997 by Böhler under different product forms (bars of 100 mm diameter and plates of 8, 14 and 25 mm thickness) and a second batch (EUROFER-2) produced in 2005 by SaarSchmiede as about 8 tons of different product forms (forgings, plates and tubes) according to slightly revised specifications.

In the following, due to the limited length of this paper, only the main observations emerged from our investigations will be reported, with a few relevant examples.

4. Unirradiated tensile properties

- No influence of product form (plates of different thickness or bars) is observed for EUROFER-1 (first batch), except for a slightly lower strength of the 25 mm plate at temperatures below RT.
- For EUROFER-2 (second batch), more scatter is observed between product forms, with the bars and the 8 mm plate delivering the worst and the best tensile properties, respectively.
- The two EUROFER batches are equivalent in terms of mechanical resistance (yield strength in Fig. 1), but EUROFER-2 exhibits better ductility (elongation and reduction of area).
- In the unirradiated condition, EUROFER shows equivalent strength and ductility (yield strength in Fig. 2) to other RAFM steels, such as F82H-mod, JLF-1, CLAM and OPTIFER.

5. Irradiated tensile properties

5.1. Dose dependence

- A steep increase with dose of irradiation hardening up to ~10 dpa is observed, followed by a tendency to saturation; based on the presently available data, it is not possible yet to exactly define the saturation dose or level.
- For T_{irr} = 300 °C and above ~0.7 dpa, strain hardening capability vanishes and uniform elongation is significantly reduced (below 0.5%, Fig. 3). On the other hand, reduction of area appears to remain at sufficient levels (above 65% at 9 dpa, Fig. 4).
- Based on the limited available information to date, EUROFER-1 and EUROFER-2 exhibit the same post-irradiation tensile behaviour.

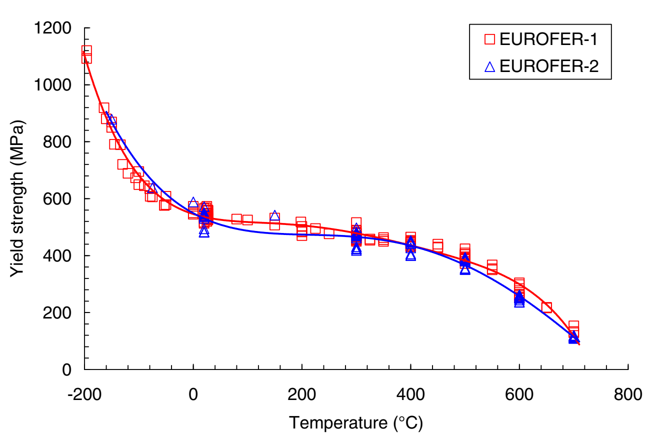

Fig. 1. Yield strength of EUROFER-1 and EUROFER-2 in the unirradiated condition.

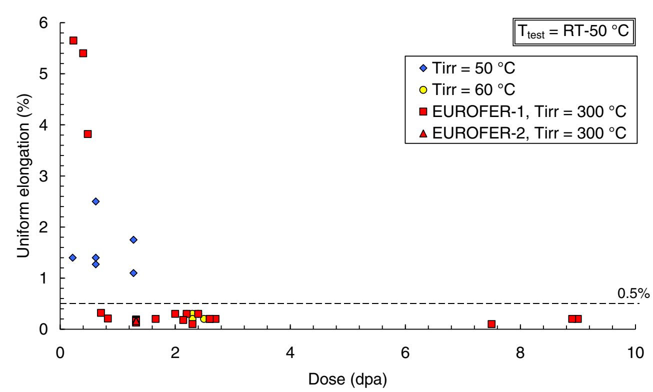

Fig. 3. Uniform elongation measured on EUROFER irradiated at different temperatures.

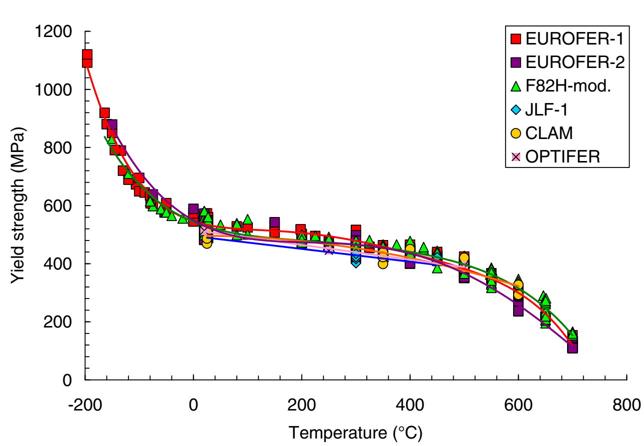

Fig. 2. Yield strength of the various investigated RAFM steels in the unirradiated condition.

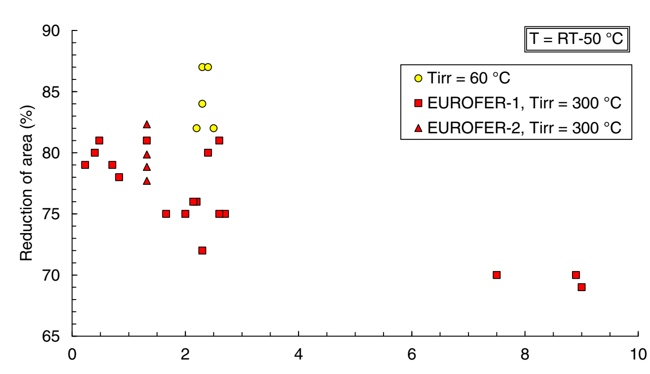

Fig. 4. Reduction of area measured on EUROFER irradiated at different temperatures.

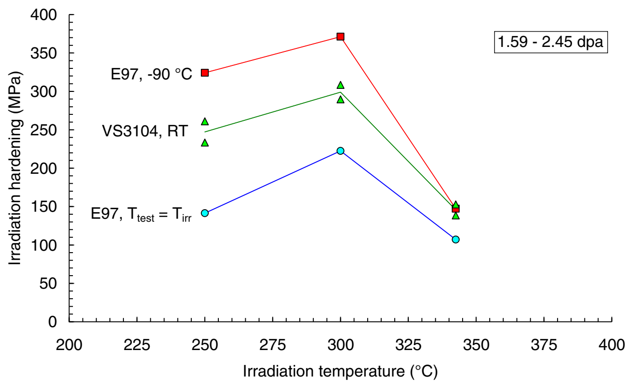

Fig. 5. Irradiation hardening measured on EUROFER and VS3104 irradiated in SUMO-09 at 250, 300 and 343 °C.

- Results from irradiations conducted between 325 and 336 °C indicate that in this range, with respect to 300 °C, partial recovery of irradiation damage is already taking place and irradiation damage is therefore mitigated.

5.2. Irradiation temperature dependence

- The available information confirms that 300 °C is the most critical irradiation temperature in terms of hardening and loss of ductility (hardening data for EUROFER and a similar 9Cr alloy, denominated VS3104, from the SUMO-09 experiment [6] in Fig. 4).
- Above 300 °C, data suggest that recombination of irradiation defects and annealing recovery start to ensue as early as 325–343 °C (Fig. 5). The same phenomena can be observed when the test temperature is higher than 400 °C.

6. Comparisons with other RAFM steels

- In the unirradiated condition, EUROFER shows equivalent tensile properties (strength and ductility) to other RAFM steels, such as F82H-mod, JLF-1, CLAM and OPTIFER.
- In the irradiated condition, only very limited comparisons could be made due to the scarcity of available data under comparable irradiation conditions. Nevertheless, it appears that EUROFER irradiated at 300 °C exhibits more hardening and comparable ductility as compared to F82H-mod and JLF-1. Further comparisons between EUROFER and F82H-mod irradiated up to 30.2 dpa at 336 °C show that EUROFER exhibits larger irradiation hardening and lower uniform elongation, but higher total elongation.

7. Future perspectives

Further insight into the tensile properties of irradiated EUROFER will be gained once post-irradiation results from recently concluded irradiation experiments (namely, SPICE and ARBOR-2) are made available.

Acknowledgements

The authors are gratefully indebted to all the colleagues who have kindly provided tensile data, even when still unpublished, namely: Jan-Willem Rensman (NRG), Ana Alamo, Fahrad Tavassoli and Jean Henry (CEA), Edeltraud Materna-Morris (FZK), Philippe Spätig (PSI), Claus Petersen (FZK) and H. Tanigawa (JAERI). This work, supported by the European Communities under the contract of Association between EURATOM/SCK•CEN, was carried out within the framework of the European Fusion Development Agreement (EFDA). The views and opinions expressed herein do not necessarily reflect those of the European Commission.

References

[1] M.S. Tillack, X.R. Wang, J. Pulsifer, S. Malang, D.K. Sze, Fus. Eng. Des. 49&50 (2000) 689.
[2] B. van der Schaaf, G. Le Marois, A. Moeslang, M. Victoria, in: 19th International Atomic Energy Agency Fusion Energy Conference, Lyon, France, 14–19 October 2002.
[3] B. van der Schaaf et al., Fus. Eng. Des. 69 (2003) 197.
[4] E. Lucon et al., Fus. Eng. Des. 81 (8–14) (2006) 917. February.
[5] E. Lucon, W. Vandermeulen, SCK•CEN Open Report BLG-1042 Rev. 1 October 2007.
[6] J.-W. Rensman, E. Lucon, H.N. Nolles, P. ten Pierick, Irradiation hardening of EUROFER and related steels at 250 °C, 300 °C, and 350 °C, Presented at ICFRM-13, Nice (France), 10–14 December 2007.