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Choice of a low operating temperature for the DEMO EUROFER97 divertor cassette

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HIGHLIGHTS

- In this article the lower limit of allowed operation temperature window was defined for reduced activation steel EUROFER97 as structural material of DEMO divertor body.
- The underlying rationale and supporting experimental data from a number of irradiation tests were presented.
- The motivation of this study was to explore the possibility to use EUROFER97 for water-cooled divertor cassette at temperatures below 350 °C.
- Literature data showed that the FTTT of EUROFER97 at 6 dpa (the expected maximum dose of cassette body after 2 fpy) is about 180 °C.
- This result imposes the guideline on the coolant inlet temperature of the divertor cassette.

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ABSTRACT

One of the fundamental input parameters required for the thermo hydraulic and structural design of a divertor cassette is the operation temperature range. In the current design activities to develop European DEMO divertor in the frame of EUROfusion, reduced activation steel EUROFER97 was chosen as structural material for the divertor cassette body considering its low long-term activation and superior creep and swelling resistance under neutron irradiation (You et al., 2016) [1]. For specifying an operation temperature range (i.e. cooling condition) various, often conflicting requirements have to be considered. In this article the lower limit of allowed operation temperature window is defined for EUROFER97 for structural design of DEMO divertor cassette body. The underlying rationale and supporting experimental data from a number of previous irradiation tests are also presented. The motivation of this survey study is to explore the possibility to use EUROFER97 for water-cooled divertor cassette at temperatures below 350 °C which has been regarded as limit temperature to preserve ductility under irradiation. Based on the literature data of FTTT (Fracture Toughness Transition Temperature) calibrated by Master Curve method, it is concluded that EUROFER97 at the envisaged maximum dose of 6 dpa will have to be operated above 180 °C taking the embrittlement due to helium production into account.

1. Introduction

The design of a Demonstration Fusion Power Reactor (DEMO) to follow ITER, with the capability of generating hundreds of MW net electricity, is viewed by fusion community as a remaining crucial step towards the exploitation of fusion power. The recent EU fusion roadmap Horizon 2020 [2] advocates for a pragmatic approach and considers a pulsed "low extrapolation" DEMO. This should be based on mature technologies and reliable regimes of operation, as much as possible extrapolated from the ITER experience and on the use of materials and technologies adequate for the expected level of

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neutron fluence. In the Consortium EUROfusion a corresponding pre-conceptual design activity has now been launched.

An important component of DEMO is the Divertor (CAD contour model illustrated in Fig. 1). The essential function of the Divertor is to control the content of helium ash and other impurities in the burning plasma core by removing plasma particles from the scrape-off layer of the plasma boundary. The removal of the edge plasma is achieved by intense particle bombardment onto the Divertor Target plate producing neutral gas being pumped out. This process generates high heat flux onto the Target surface that has to be continuously removed from the Divertor Target. The required power exhaust amounts to roughly 20% of the total thermal power of the fusion plasma (including alpha power). As one of the major in-vessel components interfacing between the plasma and the Vacuum Vessel, the Divertor shall tolerate the resulting heat flux loads while providing neutron shielding to the Vacuum Vessel and the superconducting magnets in the vicinity at the same time.

In the pre-conceptual design activities for the European DEMO divertor, many materials have been proposed as for Plasma Facing components as for the divertor cassette basing on one of the fundamental design parameters such as the operation temperature range of the divertor cassette.

In general for material selection the starting point was been trying to use the same ITER material if possible. For the ITER divertor cassette the austenitic stainless steel AISI 316 L(N) IG has been used as structural material. When the nuclear fluences increase, as in ITER TBM (Test Blanket Module) or in DEMO in-vessel components, it is not possible to use AISI 316, because of high content of nickel, it is subject to strong activation. Also the swelling behaviors of ferritic and austenitic steels under neutron irradiation are very different (see Fig. 2).

9Cr steel EUROFER97 is currently considered as the structural material for the cassette body as is the case for the breeding blanket [1]. This use of EUROFER97 steel has significant advantages owing to beneficial properties such as reduced long-term activation and strong resistance against creep and swelling under intense neutron irradiation. The optimal operation temperature (thus the cooling condition) for the cassette is identified considering different and often conflicting requirements such as the type and allowed pressure of coolant, possible consequences of LOCA events (loss of coolant accident), limitation by design code rules and power conversion efficiency.

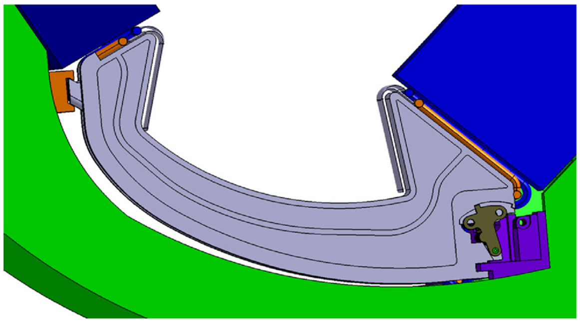

Fig. 1. CAD of DEMO divertor cassette as of 2015.

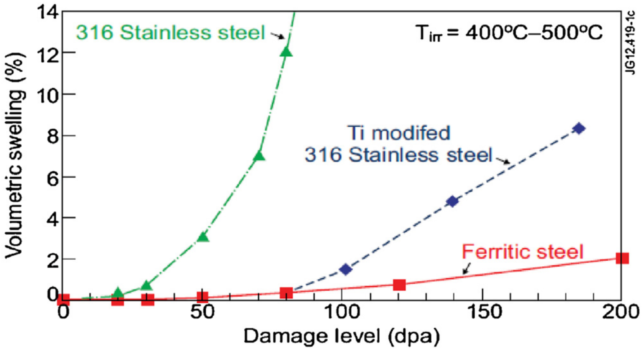

Fig. 2. Comparative swelling behavior under fission neutron irradiation for ferritic and austenitic steels [6].

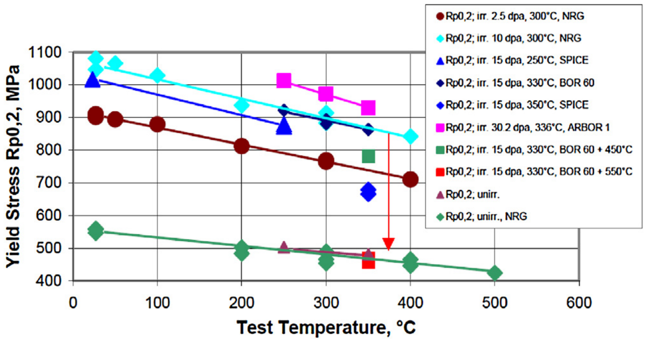

Fig. 3. Yield Stress (Rp0,2) behaviour of irradiated EUROFER 97 on dependence of test temperature compared to unirradiated data (the temperature in the legend indicates the irradiation temperature) [9].

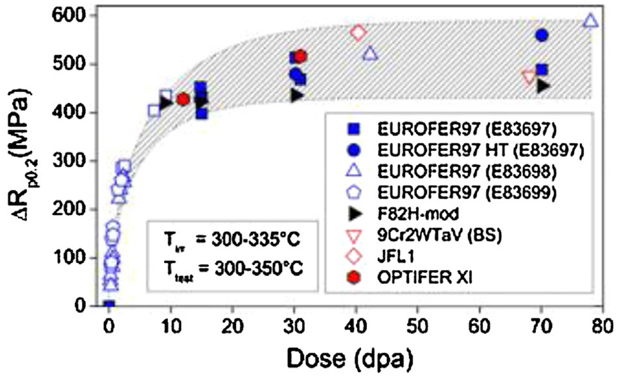

Fig. 4. Irradiation hardening vs irradiation dose for EUROFER97 and other RAFM steels [3].

In this paper, a material-based rationale to identify the allowable operation temperature range is discussed focusing on fracture mechanical properties.

2. EUROFER97 swelling and tensile properties

As discussed, reduced activation EUROFER97 and RAFM steels are the primary choice materials for first wall and breeding blanket for future fusion power plants [3–5]. This mainly 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 [6]. Furthermore, relevant advantages in terms of swelling behavior have been demonstrated under fission irradiation for ferritic steel (Fig. 2).

Lot’s information on EUROFER97 can be found in Refs. [5,7] and [8].

As regards tensile properties, EUROFER97 Yield Stress (Rp0.2) shows dependences from temperature and irradiation condition.

Fig. 3 [9] shows Yield Stress vs test temperature for EUROFER97 in the unirradiated condition and after neutron irradiation in different medium and high dose European irradiation programmes at target irradiation temperature (Tirr) between 250 and 350 °C.

The evolution of the hardening with damage dose is summarized in Fig. 4 [3]. Neutron irradiation leads to a substantial increase in the

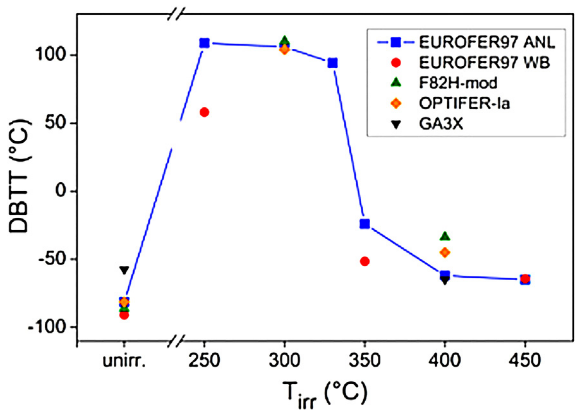

Fig. 5. DBTT vs irradiation temperature for selected RAFM steels from SPICE tests (average damage dose in Spice was 16.3 dpa) [3].

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 behavior 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.

3. EUROFER97 fracture mechanical properties and helium effect

For defining the allowable operation temperature range for DEMO divertor cassette, irradiation embrittlement has to be taken into account.

In particular the effects of temperature, irradiation and Helium production on Ductile to Brittle Transition Temperature (DBTT) and Fracture Toughness Transition Temperature (FTTT) have been investigated.

The DBTT is defined as the temperature at which the fracture energy passes below a predetermined value (Charpy impact test). Fig. 5 [3] shows the DBTT vs irradiation temperature for EUROFER97 and other RAFM steels.

The DBTT is influenced most at low irradiation temperature (T irr < 330). The evolution of the neutron irradiation induced embrittlement with dose at different irradiation temperatures is shown in Fig. 6 [3]. All RAFM steels show increase in the Δ DBTT with dose below 15 dpa.

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 further increasing the damage dose the embrittlement rate decreases and a clear tendency towards saturation is observed at the achieved damage doses.

The FTTT is defined as midpoint temperature between complete brittle fracture and complete ductile tearing behavior. Fig. 7 shows the neutron irradiation induced shift in FTTT (Fracture Toughness Transition Temperature) and KLST (specimen according to DIN 50 115) and ISO-V DBTT for EUROFER97 vs irradiation dose. Irradiation induced shifts in FTTT are significantly larger than shifts in Charpy DBTT which indicates a non-conservative estimations on the embrittlement by Charpy test.

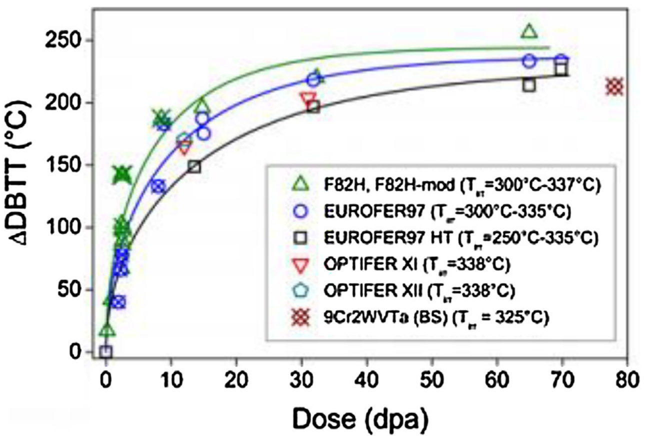

Fig. 6. Irradiation shifts of the DBTT vs dose for EUROFER97 and other RAFM steels.

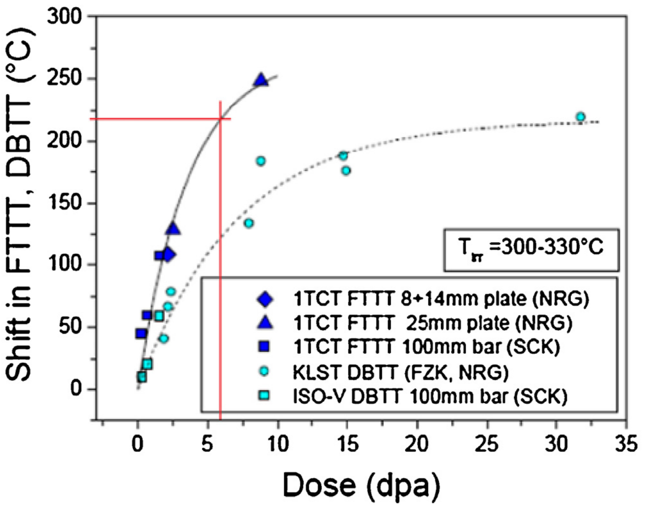

Fig. 7. Irradiation induced shift in FTTT and KLST and ISO-V DBTT for EUROFER97 [3].

There is significant uncertainty regarding the magnitude of additional embrittlement that might be introduced during fusion-relevant neutron irradiation that would generate ∼10 appm He/dpa in steels due to helium-induced hardening.

Experiments based on neutron-irradiated B-doped RAFM steels (where additional He generation is controlled by boron transmutation) indicate the increase in DBTT from He can approach or exceed the DBTT increase associated with radiation hardening at 250–350 °C.

Fig. 8 [3] shows the additional increment of DBTT increase attributable to He production following fission neutron irradiation of B-doped EUROFER97 steels.

4. DBTT and FTTT for DEMO divertor cassette in irradiation condition

In DEMO it is assumed that the divertor cassette should be replaced after no more than 2 full power years (fpy). A neutronic calculation [10] has determined the maximum irradiation damage level in the structural material of the cassette body as 6 dpa after 2 fpy. The corresponding Helium production in EUROFER97 was determined to be ∼100 appm. It can be assumed that the ductile-to-brittle (DBTT) measured in dynamical Charpy impact tests and

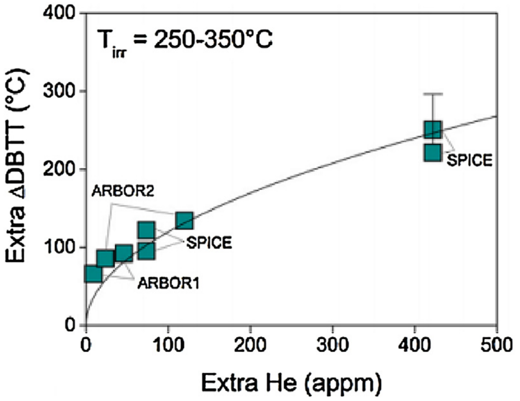

Fig. 8. Helium induced extra embrittlement vs extra helium amount for irradiated boron doped steels.

the fracture toughness (FTTT) transition temperatures quantified in quasi-static fracture-mechanical tests are correlated but experimental results show that the two transition temperatures differ to some degree.

The DBTT of EUROFER97 varies with the batch number and product form. For the 1 st batch of EUROFER97 (EUROFER97-1) the average DBTT is about −80 °C (Fig. 5).

The FTTT of EUROFER97 also varies with the batch number and product form. In addition, there is an additional uncertainty in FTTT imposed by application of the standard Master Curve methodology. For the first batch of EUROFER97 the FTTT is about −108 °C. Application of the modified Master Curve procedure [11] yields considerably higher transition temperature of −78 °C. However, since the modified master curve methodology has not been validated yet in the irradiated state, FTTT of −108 °C in the unirradiated condition is considered here.

Post-irradiation assessment both DBTT and FTTT concludes the following regarding the shift of the Transition Temperature after irradiation at 6 dpa:

- According to Fig. 6 the DBTT of EUROFER97 shifts from the unirradiated level at ∼−80 °C by ∼123 K to ∼43 °C;
- According to Fig. 7 the FTTT of EUROFER97 shifts from the unirradiated level at ∼−108 °C by ∼220 K to ∼112 °C.

However since Figs. 7 and 8 are based on material samples irradiated in fission reactors, Helium production in the material that will occur due to irradiation with high energy neutrons generated in the fusion reaction is not taken into account. In Ref. [3] a DBTT shift in the range 0.5–0.6 K/appm He is estimated on the base of Charpy impact experiments on boron doped model steels. Hence for our case of 100 appm He an additional shift of the DBTT of 50–60 K is expected. Corresponding examinations of helium effects on the FTTT shift are not known to the authors and are assumed here to be of similar magnitude. This assumption needs to be validated in future but is assumed to be conservative.

Hence for an irradiation damage of 6 dpa the DBTT of EUROFER97 is considered at ∼100 °C, the FTTT at ∼180 °C.

5. Conclusions

In this article the lower limit of allowed operation temperature window was defined for reduced activation steel EUROFER97 as structural material of DEMO divertor body. The underlying rationale and supporting experimental data from a number of irradiation tests were presented. The motivation of this survey study was to explore the possibility to use EUROFER97 for water-cooled divertor cassette at temperatures below 350 °C which has been regarded as limit temperature to preserve ductility under irradiation. Literature data based on the standard Master Curve methodology showed that the FTTT of EUROFER97 at 6 dpa (the expected maximum dose of cassette body after 2 fpy) is about 180 °C taking the embrittlement due to helium production into account. This result imposes the guideline on the coolant inlet temperature of the divertor cassette. Attention should be paid to off-normal shutdown events where the temperature path may fall below FTTT after a long-term nuclear operation.

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