Neutron Irradiation and Helium Effects in RAFM Steels

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Application - structural materials

- Structural materials for in-vessel components of future Fusion Reactors (FR) will be exposed to **high neutron** and **thermo-mechanical loads**
- **Reduced Activation Ferritic/Martensitic** (RAFM) steels are primary candidate structural materials for the First-Wall (FW) and Breeding Blanket (BB) of FR

Main radiation effects

Displacement damage

Nuclear transmutation (He, H, …)

→ Degradation of microstructure & mechanical properties, swelling, …

↓ Loss of structural integrity

Objectives

- Assessment of the **displacement damage** induced degradation of the **mechanical properties** of RAFM steels up to **70 dpa** on the base of **European irradiation campaigns**
- Assessment of **helium effects** on the base of experiments imitating helium production by applying **boron doping technique** under fission neutron irradiation or by utilizing **spallation neutron source**

Materials

- EUROFER97 - European reference structural material for ITER TBM and DEMO Blanket
- Nominal composition: Fe-8.91Cr-1.08W-0.48Mn-0.20V-0.14Ta-0.006Ti-0.12C
- Model alloys: ADS2 (82wppm nat. B), ADS3 (83wppm ^{10}B)

E. Materna-Morris, M. Klimenkov, A. Möslang, Mater. Sci. Forum (2013)

European irradiation programmes

- **KIT**: SPICE (16.3dpa @250-450°C, HFR, Petten), WTZ 01/577 (15dpa @330°C, BOR-60, Dimitrovgrad), ARBOR1&2 (32&70dpa @330°C, BOR-60, Dimitrovgrad)

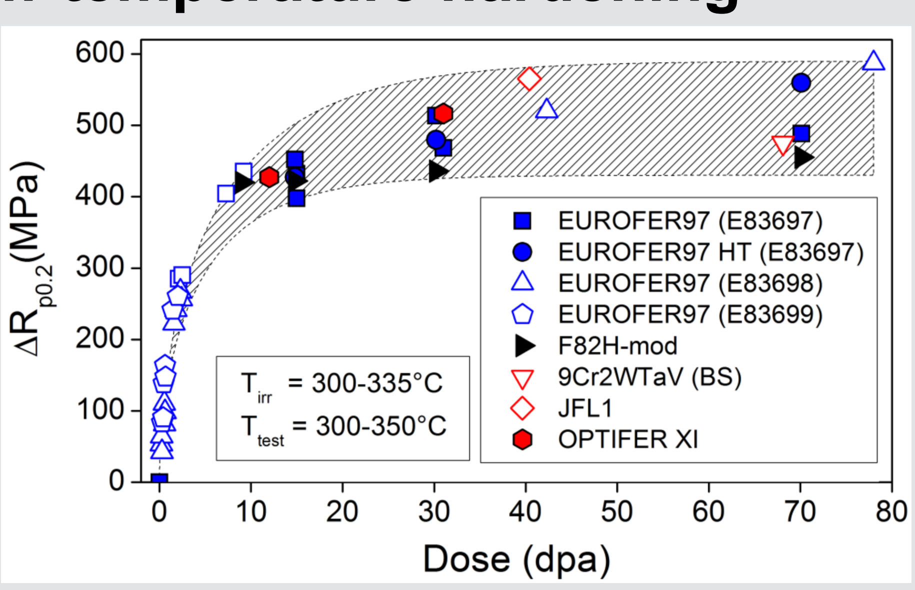
  C. Petersen, KIT, FZKA 7517 (2010)
  E. Materna-Morris, A. Möslang, H.-C. Schneider, JNM (2013)
  E. Gaganidze, J. Aktaa, FED (2013)
- **CEA**: ALTAIR (40dpa @325°C, BOR-60, Dimitrovgrad), ARBOR2 (80dpa @325°C, BOR-60, Dimitrovgrad)

  A. Alamo, J.L. Bertin, V.K. Shamardin, P. Wident, JNM (2007)
- **NRG**: SUMO-02÷07, SIWAS-06,07,09, SINAS-80/6,80/7, CHARIOT-02,04 (2.5-10dpa @300°C, 60°C, HFR, Petten)

  J. Rensman, NRG, 20023/05.68497/P (2005)
- **SCK•CEN**: IRFUMA-I, II, III (0.3-2dpa @300°C, BR2, Mol)

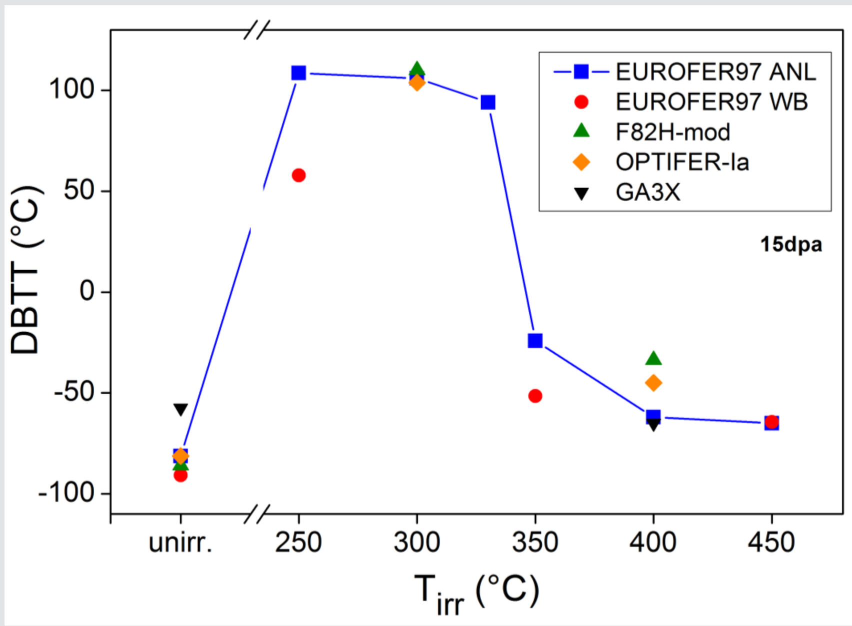
  E. Lucon, R. Chaouadi, M. Decréton, JNM (2004)

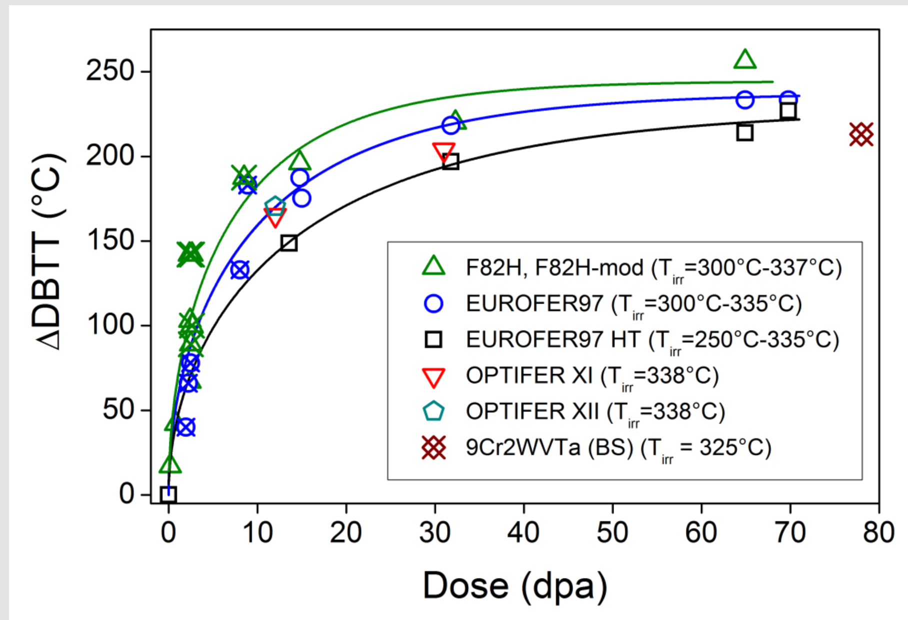
Low temperature hardening



- Steep increase of hardening with dose below 10 dpa
- Reduction of the hardening rate with hardening saturation for selected steels at the achieved doses

Radiation embrittlement

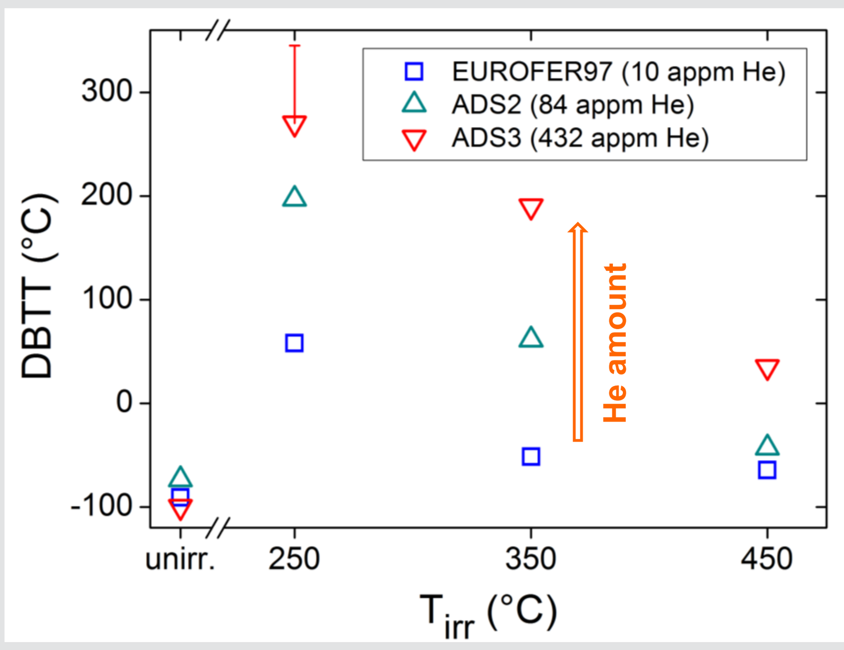


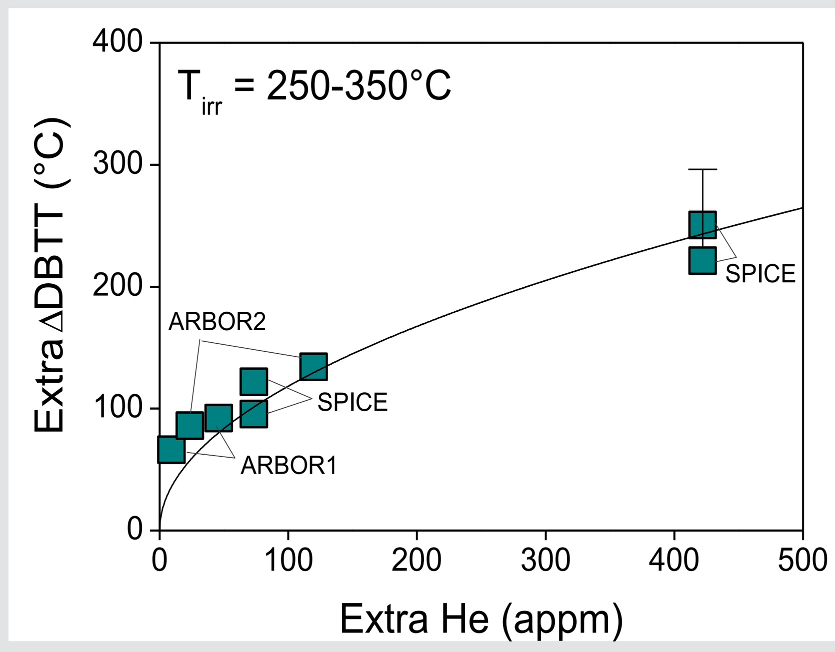


E. Gaganidze, FED (2008)

- T_{irr} ≤ 330°C: strong embrittlement
- T_{irr} ≥ 350°C: minor embrittlement
- Steep increase in the DBTT with dose below 15 dpa
- DBTT saturation at the achieved doses

Helium embrittlement





E. Gaganidze, FED (2008)

- Strong irradiation temperature dependence of helium effects
- Progressive embrittlement with increasing helium concentration (up to 430 appm) at T_{irr} ≤ 350°C

T_{irr} ≤ 350°C (boron doping technique)

❖E. Wakai N. Okubo, et al., JNM (2010): **0.4°C/appm He** (up to 300 appm)
❖E. Gaganidze, J. Aktaa, JNM (2011): **0.5°C/appm He** (up to 420 appm He)

T_{irr} < 380°C (Spallation target irradiation)

❖Y. Dai, J. Henry, et al., JNM (2011): **0.3°C/appm He** (up to 1400 appm)
0.13-0.15°C/appm He (up to 600 appm)

T_{irr} ≥ 450°C (Boron doping technique)

❖E. Gaganidze, J. Aktaa, FED (2008): **0.25°C/appm He** (up to 420 appm)

Design limits due to dpa & helium effects

Low irradiation T & fusion neutrons (10 appm He/dpa)

❖Helium embrittlement **1.5-5°C/dpa**
❖**The mechanical performance of RAFM steel mainly limited by dpa!**
❖By utilizing **post irradiation annealing** for the recovery of dpa effects helium effects tolerable up to at least **40 dpa** on the basis of spallation target irradiation

High irradiation T & fusion neutrons (10 appm He/dpa)

❖Helium embrittlement **2.5°C/dpa**
❖**Dpa effects negligible**
❖Helium effects tolerable up to **40 dpa** on the basis of boron doping experiment

The RAFM steel EUROFER97 is highly suited for fusion reactor design with operating temperature range between 350 and 550°C up to 40 dpa & 400 appm He

EUROfusion WPMAT

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