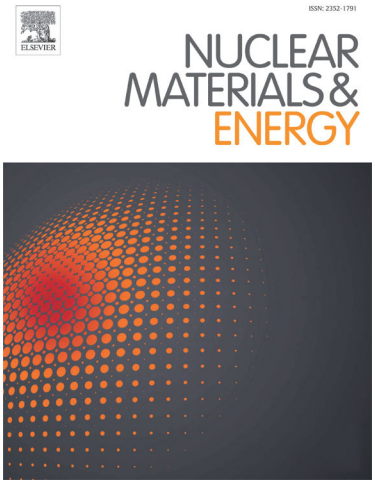
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Evolution of tensile and Charpy impact properties of EUROFER97-3 and three RAFM steels during neutron irradiation at 540 °C with increasing damage dose from 19 to 24 to 41–46 dpa

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Evolution of tensile and Charpy impact properties of EUROFER97-3 and three RAFM steels during neutron irradiation at 540 °C with increasing damage dose from 19–24 to 41–46 dpa

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The reduced-activation ferritic-martensitic (RAFM) steels EUROFER97-3 in two heat-treatment conditions (EUROFER97-3_980/780 and EUROFER97-3_1100/700), F82H, M474, and L664B were neutron irradiated in the BOR-60 fast reactor at approximately 540 °C. Tensile and Mini-Charpy impact properties were evaluated after irradiation to 41.5–45.8 dpa and compared with previously obtained results at 19.2–23.8 dpa to assess the evolution of mechanical properties with dose at the high irradiation temperature.

Tensile tests performed at 550 °C show that increasing the damage dose to 41.5–43.6 dpa does not result in systematic progressive hardening. Additional strengthening is small for EUROFER97-3_980/780, negligible for EUROFER97-3_1100/700 and L664B, and moderate for F82H and M474. No general loss of tensile ductility is observed.

The Charpy impact results show a similarly non-monotonic dose dependence. Between 21.6–23.8 and 43.6–45.8 dpa, the upper-shelf energy remains essentially unchanged for all investigated material conditions. The ductile-to-brittle transition temperature is nearly stable for EUROFER97-3_980/780 and M474, decreases for EUROFER97-3_1100/700 and F82H, and shows only a small increase for L664B.

Overall, the tensile and Charpy results indicate a tendency toward stabilization of the mechanical properties of the investigated RAFM steels as the damage dose increases from approximately 20 to more than 40 dpa at 540 °C. The absence of monotonic hardening and embrittlement is consistent with the increasing importance of thermally activated recovery and concurrent microstructural evolution at this irradiation temperature.

Keywords: RAFM steels; neutron irradiation; tensile properties; Charpy impact properties; damage dose; upper-shelf energy; ductile-to-brittle transition temperature

1. Introduction

This study continues the experimental programme reported in [1–4] within the framework of European fusion materials and blanket-development activities [5–9]. RAFM steels are reference structural materials for fusion blanket applications because of their reduced activation and favorable thermophysical and swelling behavior; their irradiation response nevertheless depends strongly on irradiation temperature, accumulated dose, and initial microstructure [10].

Neutron-irradiation studies of EUROFER97 and related RAFM steels have shown pronounced hardening and embrittlement at lower irradiation temperatures, while the dose dependence may become weaker or approach saturation at sufficiently high accumulated damage [11–14]. In BOR-60, mechanical properties of RAFM steels have been investigated to 70–80 dpa, providing an important high-dose reference for the evolution of strength, ductility, and ductile-to-brittle

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transition behavior [15, 16]. Microstructural investigations of irradiated EUROFER97 further demonstrate that the population and character of irradiation-induced defects vary strongly with temperature and are directly related to mechanical-property changes [17-21].

Our previous work established the tensile and Charpy impact response of the present EUROFER97-3 material after irradiation at 330 and 540 °C to approximately 20 dpa [1, 2, 4]. The present study extends the high-temperature branch of this programme to 41–46 dpa and, together with F82H, M474, and L664B, examines whether increasing the accumulated damage from approximately 20 to more than 40 dpa at about 540 °C produces progressive hardening and embrittlement or instead a tendency toward stabilization of the mechanical properties.

2. Experimental

2.1. Materials, heat treatments, specimens

In this study, the following RAFM steels were irradiated and examined.

EUROFER97-3

The EUROFER97-3 plate (ID45) used in this work (dimensions: 2490 × 1015 × 33.3 mm) was produced by Saarschmiede Freiformschmiede GmbH through a manufacturing route consisting of:

• primary melting in a vacuum induction furnace;

• secondary melting via vacuum arc remelting;

• forging to a billet of roughly Ø150 × 700 mm;

• cropping of the billet's top and bottom ends to remove surface and forging defects;

• subsequent rolling on a trio mill to plate form;

• quality heat treatment.

Tensile [1] (Figure 1a) and Mini-Charpy (KLST) impact bending [2] (Figure 1b) specimens were machined from this plate together with creep [3] specimens. Two sets of the tensile and Charpy impact specimens were produced, each subjected to a different heat-treatment schedule (see Table 1) at KIT. All specimens were oriented such that the rolling direction lay perpendicular to the specimen axis.

The chemical composition of EUROFER97-3 is presented in Table 2. Measurements performed at KIT (third column) show that the material meets the specified delivery requirements (second column).

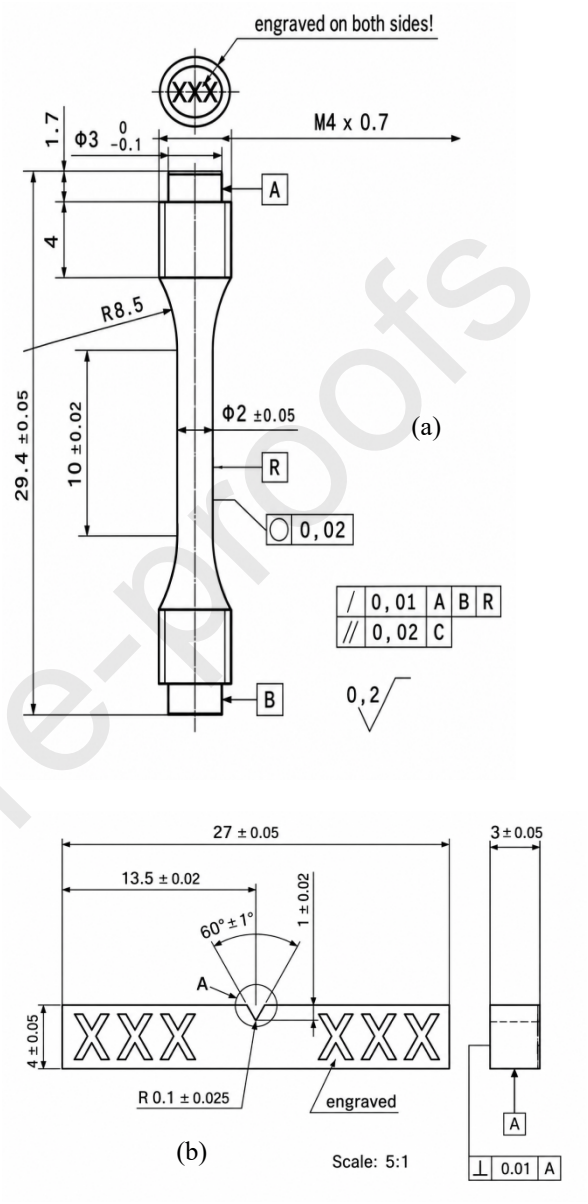


Figure 1. Tensile (a) and Charpy impact (b) specimens for irradiation testing in the BOR-60 reactor. All dimensions are in mm

Table 1. Heat treatments of RAFM steels studied

Grade	Austenitization	Quenching	Tempering	Final cooling
EUROFER97-	1100°C, 30 min	air	700°C,	air

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3_1100/700			120 min	
EUROFER97-3_980/780	980°C, 30 min	air	780°C, 120 min	air
F82H	960°C, 30 min	air	750°C, 60 min	air
M474	880°C, 30 min	water	750°C, 120 min	air
L664B	1000°C, 30 min	air	760°C, 90 min	air

Table 2. Chemical composition of EUROFER97-3 in wt.%

Element	Specification	Analysis
Cr	8.50-9.50	9.00±0.19
C	0.090-0.120	0.102±0.009
N	0.015-0.045	0.0350±0.0074
O	0.01	0.0004±0.0001
B	0.002	0.0004±0.0001
Al	0.01	0.0015±0.0003
Si	<0.05	0.0184±0.0008
P	0.005	0.0017±0.0003
Ti	<0.02	0.00018±0.00002
V	0.15-0.25	0.2117±0.0044
Mn	0.20-0.60	0.529±0.009
Fe	not defined	87.5±2.6
Co	0.01	0.0020±0.0003
Ni	0.01	0.0099±0.0005
Cu	0.01	0.0015±0.0002
Nb	0.005	<0.0004
Mo	0.005	0.0021±0.0003
Ta	0.10-0.14	0.125
W	1.0-1.2	1.152±0.040

F82H

F82H was normalized at 960 °C for 30 min, followed by tempering at 750 °C for 60 min and the final cooling in air (see Table 1). Table 3 summarizes its chemical composition.

Table 3. Chemical composition of F82H in wt.%

Element	Analysis
Cr	8.00
C	0.091
N	0.016
O	0.001
B	0.002
Al	<0.007

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Si	0.17
P	0.009
Ti	<0.003
V	0.19
Mn	0.46
Fe	balance
Co	<0.01
Ni	<0.01
Cu	0.0015±0.0002
Nb	<0.005
Mo	<0.01
Ta	0.03
W	1.88

M474

M474 is referred to as "Lab-cast EUROFER (M474)" in [13]. Its heat treatment consisted of 880 °C for 30 min followed by water quenching (WQ), tempering at 750 °C for 120 min, and air cooling (AC) (see Table 1).

The chemical composition of M474 is shown in Table 4.

Table 4. Chemical composition of M474 in wt.%

Element	Analysis
Cr	9.124
C	0.112
N	0.00123
O	0.0014
Al	0.0063
Si	0.006
P	0.0062
Ti	0.0014
V	0.24
Mn	0.408
Fe	89.004
Ni	0.005
Cu	0.0063
Nb	0.002
Mo	0.0018
Ta	0.085
W	0.977

L664B

The analyzed compositions are given in Table 5.

L664B was normalized at 1000 °C for 30 min and subsequently tempered at 760 °C for 90 min, followed by cooling in air (see Table 1).

Table 5. Chemical composition of L664B in wt.%

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Element	Specification	Analysis
Cr	8.50-9.50	8.888
C	0.090-0.120	0.1053
N	0.005-0.015	0.0082
B	0.0105-0.0175	0.0144
V	0.17-0.23	0.222
Mn	0.90-1.10	0.9850
Ta	0.10-0.14	0.097
W	0.10-0.14	0.097
Si	< 0.05	0.0321
P	<0.005	0.0037
S	<0.005	0.0016
Al	<0.015	0.0034
Ti	<0.02	0.005
Nb	<0.0075	0.001
Cu	<0.02	0.0107
Ni	<0.025	0.006
O	<0.01	0.0086
Mo	<0.0075	0.0026
Co	<0.0015	0.0015

2.2. Irradiation

The EUROFER97-3, F82H, M474, and L664B tensile and Charpy impact specimens were irradiated in the BOR-60 fast reactor in direct contact with the circulating sodium coolant [22]. The present paper considers the high-temperature irradiation condition, with a nominal irradiation temperature of 550 °C (approximately 540 °C for the specimen positions). The cumulative irradiation parameters for the tensile and Charpy specimens are summarized in Tables 6 and 7, respectively, for each material condition; the corresponding nominal and calculated temperatures are also provided.

Table 6. Irradiation parameters for tensile specimens of the RAFM steels

Grade	T_{irr}, °C target/ actual	Neutron fluence F, $\times 10^{26}$ m^{-2}, E>0.1 MeV	NRT damage dose D, dpa
EUROFER97-3_1100/700	550/540	9.17	41.5
EUROFER97-3_980/780	550/540	9.17	41.5
F82H	550/540	9.17	41.5
M474	550/540	9.64	43.6
L664B	550/540	9.64	43.6

Table 7. Irradiation parameters for Charpy impact specimens of the RAFM steels

Grade	T_{irr}, °C target/ actual	Neutron fluence F, $\times 10^{26}$ m^{-2}, E>0.1 MeV	NRT damage dose D, dpa
EUROFER97-3_1100/700	550/540	10.11	45.8

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EUROFER97-3_980/780	550/540	10.11	45.8
F82H	550/540	9.64	43.6
M474	550/540	9.64	43.6
L664B	550/540	9.64	43.6

The specimens were housed in perforated capsules, allowing direct contact with the circulating liquid sodium. The irradiation temperature was evaluated from the sodium-coolant conditions and thermal calculations. During the final high-dose irradiation stage, the calculated temperature range in the high-temperature rig was approximately 522–576 °C, and 540 °C as an average value.

The irradiation conditions were evaluated using established data on energy deposition in the materials and neutron flux levels within the reactor channels. The estimated uncertainty of the temperature calculations is approximately ±10%, while the neutron flux uncertainty is approximately ±20%. The damage dose, calculated for iron using the NRT (Norgett–Robinson–Torrens) methodology, was determined from the precise axial positions of the tensile and Charpy impact specimens within the irradiation channels.

2.3. Tensile testing

Tensile testing before and after irradiation was performed using a Zwick universal testing machine (UTM) installed in a hot cell. The UTM was equipped with:

- a high-temperature testing system with vacuum capability and a water-cooled inert-gas chamber, together with a temperature controller for monitoring and maintaining the specimen temperature during testing;

- an extensometer with ceramic probe tips, enabling instrumented testing from room temperature to 800 °C.

The RAFM steel specimens were tested at room temperature in air and at 550 °C in argon at an actuator movement rate of 1 mm/min (nominal strain rate 8.3×10^{-4} s^{-1}). Up to three tensile specimens were tested for each material condition and test temperature; unsuccessful tests were excluded from the analysis. The 0.2%-offset yield stress ($\sigma_{0.2}$), ultimate tensile strength (UTS), uniform elongation, and total elongation were determined from the recorded load–displacement data.

2.4. Charpy impact testing

Mini-Charpy impact tests were performed in a hot cell using an instrumented Zwick 5113 impact tester with:

• support span of 22 mm

• a 15 J pendulum and a 2-mm-radius instrumented striker;

• specimen temperature control from –190 to 680 °C;

• a pneumatic system for transferring specimens from storage to the thermostat and then to the test supports.

During each test, the force-time curve was recorded and used to determine the impact energy (fracture work). The specimen temperature reported in the protocol accounts for temperature changes during transfer to the supports and before impact. Testing followed ISO-CD 14556:2000(E).

3. Results

3.1. Tensile properties after irradiation at 540 ºC up to 41.5–43.6 dpa

Figure 2 compares representative stress-strain curves obtained at 550 °C in the unirradiated and high-dose irradiated conditions. The response to irradiation is material dependent. EUROFER97-3_980/780, F82H, and M474 show increases in both yield stress and UTS, whereas the strength of EUROFER97-3_1100/700 changes only slightly. L664B also shows a relatively small change in yield stress, accompanied by a more pronounced increase in UTS. No pronounced irradiation-induced loss of tensile ductility is observed at this test temperature. For several material conditions, the irradiated curves exhibit even higher uniform and/or total elongation than in the unirradiated state.

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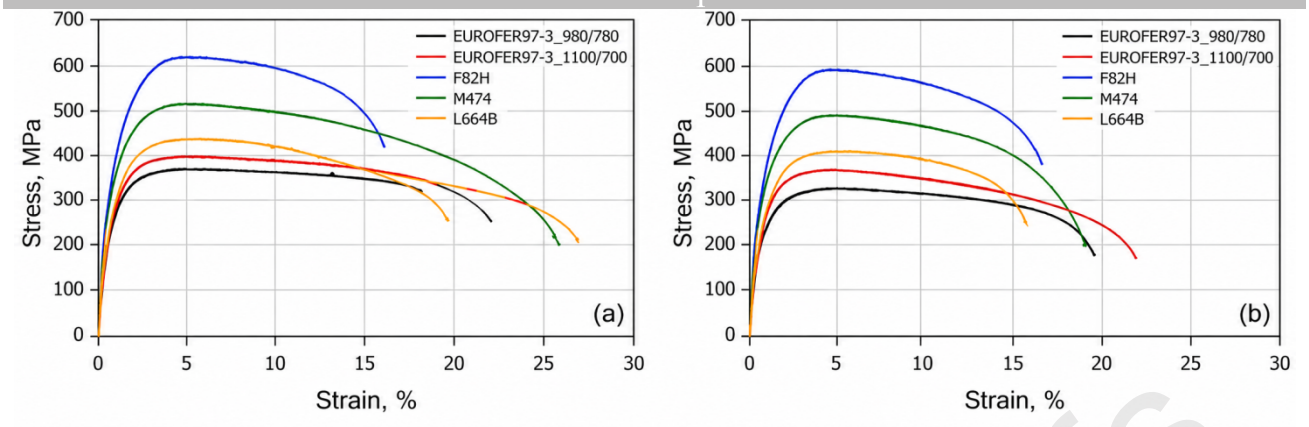


Figure 2. Representative stress-strain diagrams of (a) EUROFER97-3 in 980/780 and 1100/700 heat-treatment conditions and (b) F82H, M474, and L664B before and after irradiation at 540 °C. The irradiation doses were 41.5 dpa for both EUROFER97-3 conditions and F82H, and 43.6 dpa for M474 and L664B. Tensile tests were performed at 550 °C. For each irradiated condition, the representative curve was selected as that showing the closest overall agreement with the mean yield strength, UTS, uniform elongation, and total elongation of the corresponding specimen group. Arrows indicate the direction of the irradiation-induced changes

The quantitative tensile properties are summarized in Figure 3. After irradiation to 41.5–43.6 dpa, the mean yield stresses at 550 °C range from approximately 370 MPa for EUROFER97-3_980/780 and 376 MPa for M474 to 519 MPa for EUROFER97-3_1100/700 (see Figure 3 a). The corresponding UTS values range from approximately 414–415 MPa for EUROFER97-3_980/780 and M474 to 575 MPa for EUROFER97-3_1100/700. F82H and L664B occupy intermediate strength levels (see Figure 3 b).

The strongest increase relative to the unirradiated condition is observed for M474. In contrast, the high initial strength of EUROFER97-3_1100/700 is essentially retained without additional irradiation hardening. The changes in L664B are also comparatively small in terms of yield stress.

The uniform elongation after high-dose irradiation remains between approximately 1.8 and 2.8 % for all investigated steels (see Figure 3 c). Total elongation remains relatively high, ranging from approximately 16–17% for EUROFER97-3_1100/700 and L664B to approximately 25–26% for EUROFER97-3_980/780 and M474 (see Figure 3 d). Although total elongation decreases for some material conditions relative to the unirradiated state, substantial tensile ductility is retained after irradiation to more than 40 dpa at 540 °C.

Tables 8 and 9 provide the individual and average results after testing at 550 °C, respectively. The relatively small scatter in the strength characteristics confirms good reproducibility of the high-dose tensile data, whereas the scatter in total elongation is naturally larger.

Tables 10 and 11 show the individual and average results at room testing temperature, respectively. The room-temperature data are included primarily to provide a complete record of the high-dose tensile tests; the following analysis focuses on the tests at 550 °C, close to the irradiation temperature.

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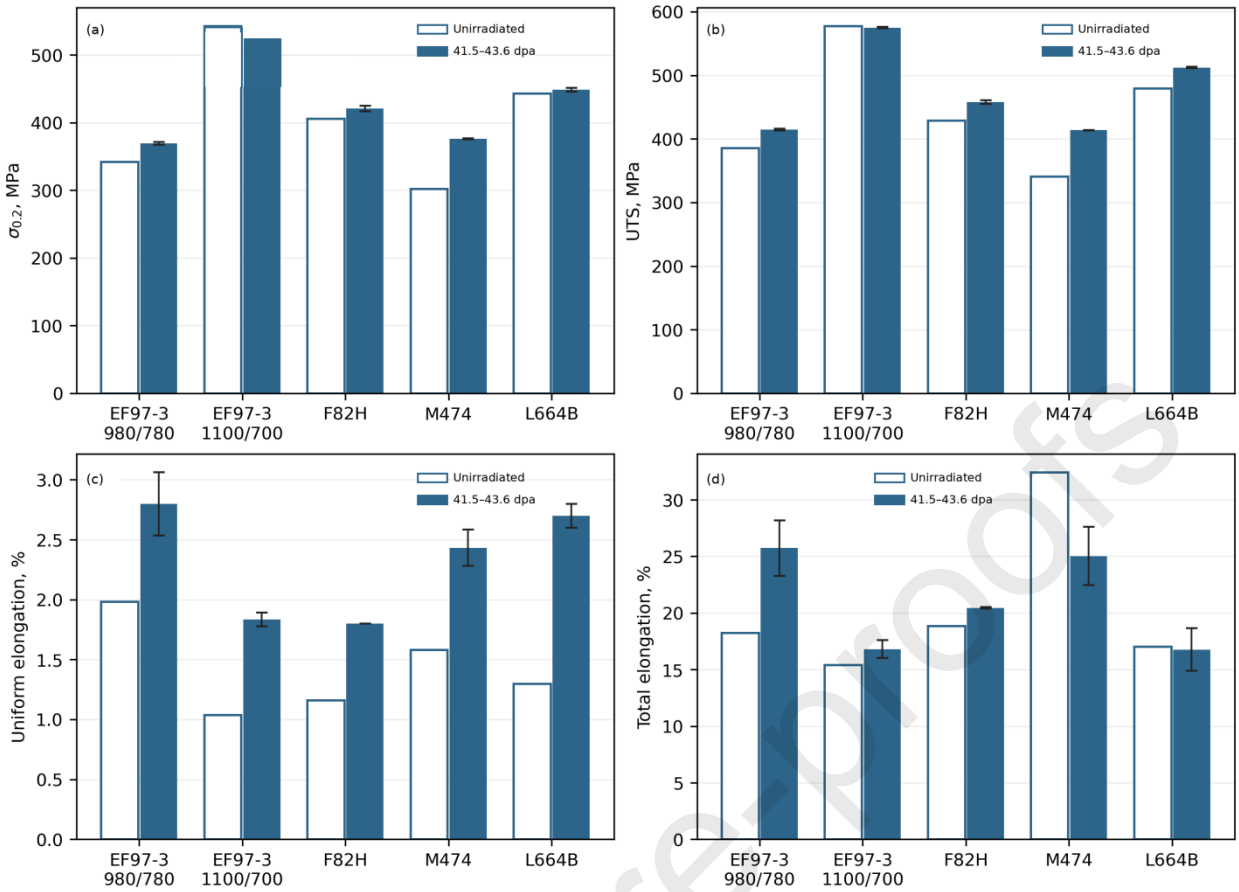


Figure 3. Tensile properties of EUROFER97-3_980/780, EUROFER97-3_1100/700, F82H, M474, and L664B in the unirradiated condition (open bars) and after irradiation at 540 °C to 41.5–43.6 dpa (filled bars): (a) 0.2%-offset yield stress, $\sigma_{0.2}$; (b) UTS; (c) uniform elongation; and (d) total elongation. Tensile tests were performed at 550 °C. Irradiated values represent the means of all successfully tested specimens for each material condition; error bars indicate one standard deviation

Table 8. Tensile properties of the RAFM steels after irradiation at 540 °C to 41.5–43.6 dpa and tensile testing at 550 °C. Individual specimen values are reported

Grade/Heat treatment	Dose, dpa	$\sigma_{0.2}$, MPa	UTS, MPa	Uniform elongation, %	Total elongation, %	Representative +/-
EUROFER97-3_980/780	41.5	372	415	2.7	22.9	
EUROFER97-3_980/780	41.5	369	416	3.1	27.2	+
EUROFER97-3_980/780	41.5	368	413	2.6	27.1	
EUROFER97-3_1100/700	41.5	519	575	1.8	15.9	+
EUROFER97-3_1100/700	41.5	520	574	1.8	17.1	

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EUROFER97-3_1100/700	41.5	518	576	1.9	17.4	
F82H	41.5	424	460	1.8	17.1	+
F82H	41.5	418	456	1.8	20.4	
M474	43.6	376	414	2.3	22.7	+
M474	43.6	376	414	2.6	27.8	
M474	43.6	377	413	2.4	24.6	
L664B	43.6	446	513	2.7	14.7	
L664B	43.6	450	513	2.8	17.2	+
L664B	43.6	451	511	2.6	18.4	

Table 9. Tensile properties of the RAFM steels after irradiation at 540 °C to 41.5–43.6 dpa and tensile testing at 550 °C. Group mean ± sample standard deviation (SD) are reported

Grade/Heat treatment	Dose, dpa	$\sigma_{0.2}$, MPa	UTS, MPa	Uniform elongation, %	Total elongation, %
EUROFER97-3_980/780 (mean ± SD; n=3)	41.5	369.7 ± 2.1	414.7 ± 1.5	2.8 ± 0.3	25.7 ± 2.5
EUROFER97-3_1100/700 (mean ± SD; n=3)	41.5	519.0 ± 1.0	575.0 ± 1.0	1.8 ± 0.0	16.8 ± 0.8
F82H (mean ± SD; n=2)	41.5	421.0 ± 4.2	458.0 ± 2.8	1.8 ± 0.0	18.8 ± 2.3
M474 (mean ± SD; n=3)	43.6	376.3 ± 0.6	413.7 ± 0.6	2.4 ± 0.2	25.0 ± 2.6
L664B (mean ± SD; n=3)	43.6	449.0 ± 2.6	512.3 ± 1.2	2.7 ± 0.1	16.8 ± 1.9

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Table 10. Tensile properties of the RAFM steels after irradiation at 540 °C to 41.5–43.6 dpa and tensile testing at room temperature. Individual specimen values are reported

Grade/Heat treatment	Dose, dpa	$\sigma_{0.2}$, MPa	UTS, MPa	Uniform elongation, %	Total elongation, %
EUROFER97-3_980/780	41.5	519	717	9.7	28.1
EUROFER97-3_980/780	41.5	519	716	9.5	25.4
EUROFER97-3_980/780	41.5	531	720	8.2	21.7
EUROFER97-3_1100/700	41.5	726	907	6.1	15.8
EUROFER97-3_1100/700	41.5	728	904	6.5	15.8
EUROFER97-3_1100/700	41.5	733	907	6	14.1
F82H	41.5	586	742	6.8	17.4
F82H	41.5	589	747	6.6	16.9
M474	43.6	544	715	7.7	22
M474	43.6	527	706	8.3	23.4
L664B	43.6	633	826	6.7	14.4
L664B	43.6	636	824	6.6	15.9

Table 11. Tensile properties of the RAFM steels after irradiation at 540 °C to 41.5–43.6 dpa and tensile testing at room temperature. Group mean ± sample standard deviation (SD) are reported

Grade/Heat treatment	Dose, dpa	$\sigma_{0.2}$, MPa	UTS, MPa	Uniform elongation, %	Total elongation, %
EUROFER97-3_980/780 (mean ± SD; n=3)	41.5	523.0 ± 6.9	717.7 ± 2.1	9.1 ± 0.8	25.1 ± 3.2

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EUROFER97-3_1100/700 (mean ± SD; n=3)	41.5	729.0 ± 3.6	906.0 ± 1.7	6.2 ± 0.3	15.2 ± 1.0
F82H (mean ± SD; n=2)	41.5	587.5 ± 2.1	744.5 ± 3.5	6.7 ± 0.1	17.1 ± 0.4
M474 (mean ± SD; n=2)	43.6	535.5 ± 12.0	710.5 ± 6.4	8.0 ± 0.4	22.7 ± 1.0
L664B (mean ± SD; n=2)	43.6	634.5 ± 2.1	825.0 ± 1.4	6.7 ± 0.1	15.2 ± 1.1

3.2. Charpy impact properties after irradiation at 540 °C up to 43.6–45.8 dpa

Figure 4 compares the Charpy impact-energy transition curves in the unirradiated condition and after irradiation to 43.6–45.8 dpa. The high-dose irradiation response differs considerably among the investigated material conditions.

EUROFER97-3_980/780 retains a transition curve at very low temperatures and a relatively high upper-shelf energy (see Figure 4 a). EUROFER97-3_1100/700 exhibits a distinctly higher DBTT and lower USE than EUROFER97-3_980/780; however, these differences are already characteristic of their respective unirradiated conditions and therefore should not be interpreted solely as irradiation effects.

F82H and M474 also retain well-defined transition behavior after high-dose irradiation (see Figure 4 b). M474 is characterized by a particularly low DBTT and relatively high USE. L664B exhibits the highest DBTT and the lowest high-dose USE among the investigated material conditions.

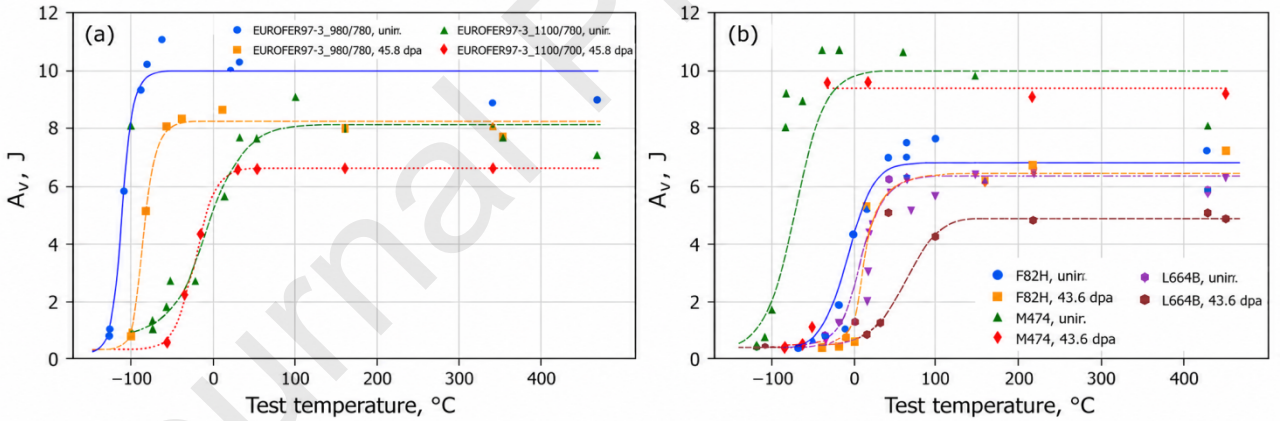


Figure 4. Impact energy, Av, as a function of test temperature for (a) EUROFER97-3_980/780 and EUROFER97-3_1100/700 and (b) F82H, M474, and L664B in the unirradiated condition and after irradiation at 540 °C. The irradiation dose was 45.8 dpa for both EUROFER97-3 conditions and 43.6 dpa for F82H, M474, and L664B

The fitted DBTT and USE values are summarized in Figure 5. The results demonstrate that the absolute Charpy properties after high-dose irradiation are strongly material dependent. Importantly, however, comparison with the corresponding unirradiated states shows that irradiation at 540 °C does not produce a common trend toward severe high-dose embrittlement. The evolution with accumulated dose is considered in Section 4.2.

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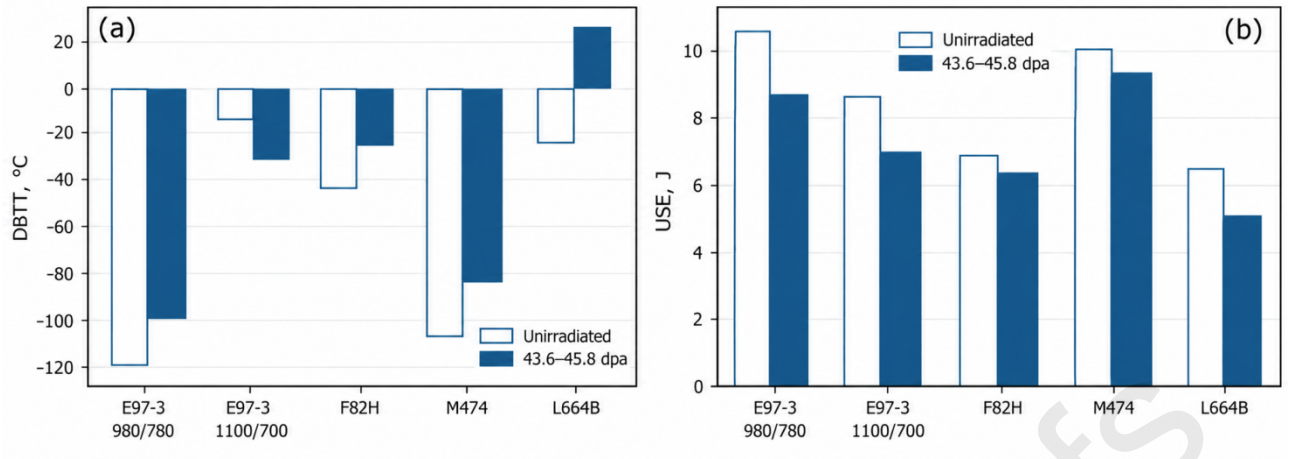


Figure 5. (a) Ductile-to-brittle transition temperature (DBTT) and (b) upper-shelf energy (USE) of EUROFER97-3_980/780, EUROFER97-3_1100/700, F82H, M474, and L664B in the unirradiated condition (open bars) and after irradiation at 540 °C (filled bars). The irradiation dose was 45.8 dpa for both EUROFER97-3 conditions and 43.6 dpa for F82H, M474, and L664B. Values are fitted point estimates; confidence intervals are not shown

4. Discussion

4.1. Evolution of tensile properties after irradiation at 540 °C from 19.2–23.8 dpa to 41.5–43.6 dpa

Figure 6 shows the measured tensile properties at 550 °C (without fitting or interpolation between the two dose levels) after the first irradiation stage, corresponding to 19.2–23.8 dpa, with those obtained after accumulation of 41.5–43.6 dpa. Increasing the damage dose by approximately a factor of two does not lead to progressive irradiation hardening common to all investigated RAFM steels.

For EUROFER97-3_980/780, the increase in dose from 19.2 to 41.5 dpa produces only a modest additional increase in strength: the yield stress increases from approximately 361 to 370 MPa and UTS from approximately 402 to 415 MPa (see Figure 6 a,b). At the same time, uniform and total elongation increase rather than decrease (see Figure 6 c,d).

EUROFER97-3_1100/700 behaves differently. Its already high strength after the first irradiation stage remains essentially stable at the higher dose: the yield stress changes from approximately 528 to 519 MPa and UTS from 578 to 575 MPa (see Figure 6 a,b). Uniform elongation increases slightly, while the change in total elongation is small (see Figure 6 c,d).

Thus, despite their very different initial heat treatments and absolute strength levels, both EUROFER97-3 conditions show no indication of progressive degradation of tensile properties between approximately 20 and 40 dpa.

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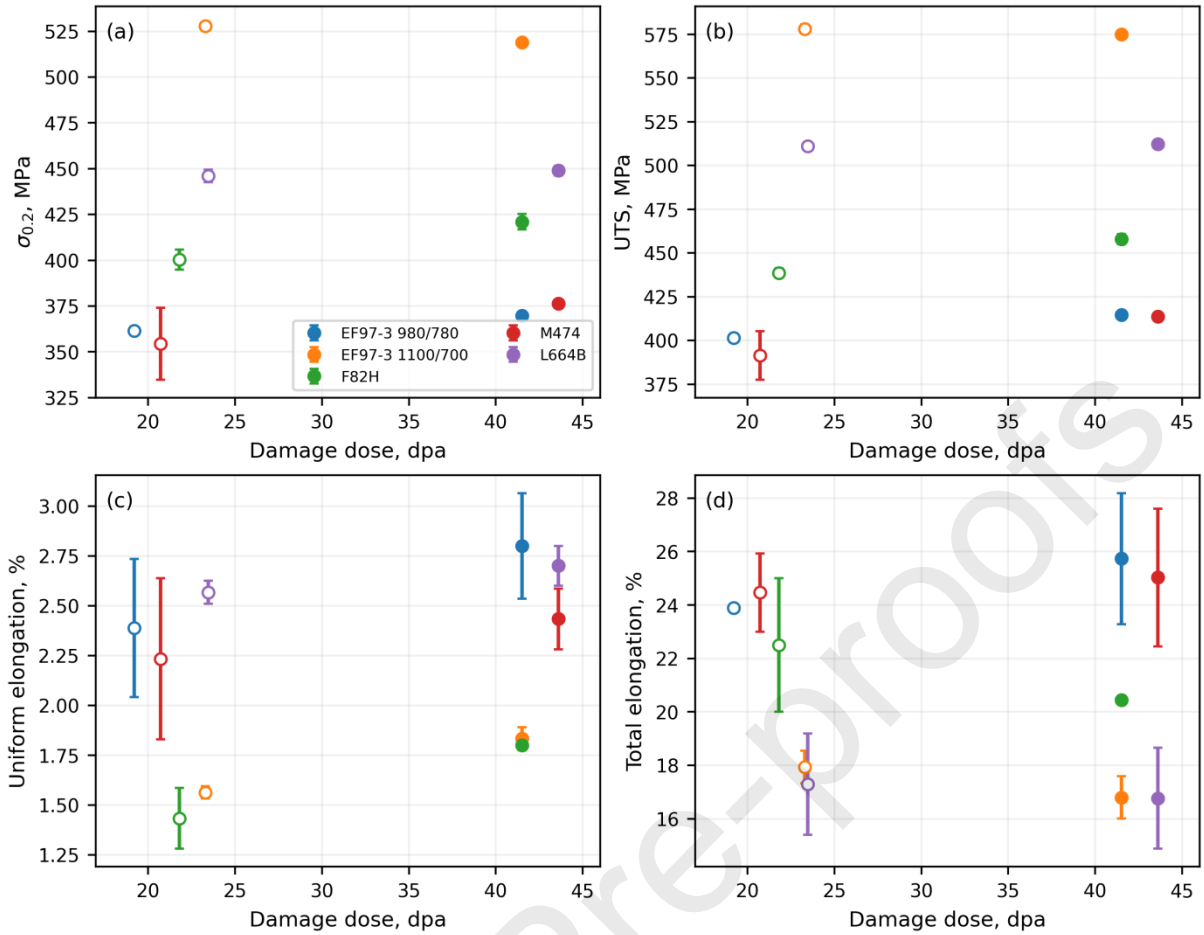


Figure 6. Comparison of tensile properties of EUROFER97-3_980/780, EUROFER97-3_1100/700, F82H, M474, and L664B at an irradiation temperature of 540 °C with increasing damage dose from 19.2–23.8 dpa to 41.5–43.6 dpa:

(a) yield strength $\sigma_{0.2}$; (b) UTS; (c) uniform elongation; (d) total elongation

The same conclusion can be extended to the other RAFM steels, although the magnitude and direction of individual changes differ. F82H and M474 exhibit moderate additional increases in yield stress and UTS with increasing dose (see Figure 6 a,b), whereas the strength characteristics of L664B remain nearly unchanged.

The corresponding changes in tensile properties are summarized in Figure 7 [1, 4]. The largest additional hardening between the two irradiation stages is observed for F82H and M474 (see Figure 7 a,b). Nevertheless, even for these materials the increase is moderate: approximately 5–6 % for the strength characteristics. EUROFER97-3_980/780 shows only about 2–3 % additional strengthening, while EUROFER97-3_1100/700 and L664B essentially reach a saturation level.

Even more important is the absence of progressive tensile embrittlement. Uniform elongation increases between the two dose levels for all five material conditions, whereas total elongation either increases or changes only moderately (see Figure 7 c,d). F82H shows some reduction in total elongation, but its value remains about 20%, i.e. at a high absolute level.

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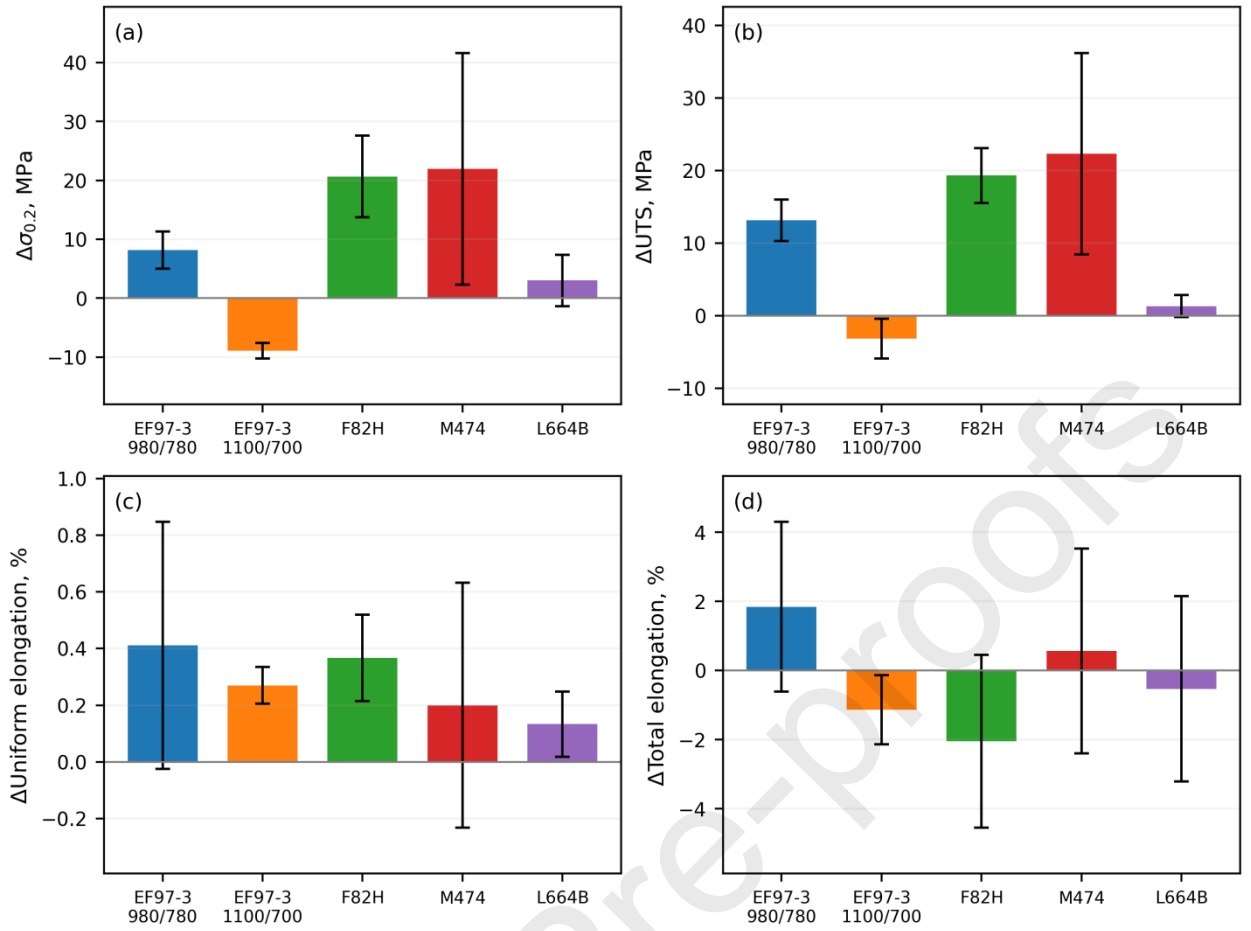


Figure 7. Changes in tensile properties of the investigated RAFM steels between the first (19.2–23.8 dpa) and second (41.5–43.6 dpa) irradiation stages at 540 °C:

(a) yield strength $\sigma_{0.2}$; (b) UTS; (c) uniform elongation; (d) total elongation

The observed behavior suggests that, at 540 °C, the mechanical response is governed not only by the accumulation of irradiation defects but also by their thermally activated recovery and by concurrent evolution of the complex ferritic-martensitic microstructure. Consequently, increasing the damage dose does not necessarily result in a monotonic increase in hardening. Such competition between defect accumulation and temperature-dependent microstructural evolution is consistent with the broader irradiation behavior reported for ferritic-martensitic steels [10] and with microstructure-mechanical-property correlations established for neutron-irradiated EUROFER97 [16].

The different responses of the five material conditions are consistent with their different initial microstructures resulting from chemical composition and heat treatment. In particular, the two EUROFER97-3 conditions provide a useful demonstration of this effect because their chemical composition is identical while their heat treatments, and consequently their initial microstructures and mechanical properties, differ substantially. The high-strength EUROFER97-3_1100/700 condition shows essentially no additional hardening above approximately 20 dpa, whereas the softer 980/780 condition exhibits only weak further strengthening.

At present, however, the tensile data alone do not allow the observed high-dose evolution to be assigned to a particular microstructural mechanism. Possible contributions include recovery and rearrangement of irradiation-induced defect structures and dose-dependent evolution of precipitate and dislocation substructures. Irradiation-induced dislocation-loop populations and other defect structures are known to contribute to the radiation hardening in EUROFER97 [16,19-21]; microstructural characterization of the present high-dose specimens is therefore required before a more specific mechanism can be established.

4.2. Evolution of Charpy impact properties after irradiation at 540 °C from 21.6–23.8 dpa to 43.6–45.8 dpa

Figure 8 compares the impact-energy transition curves from the earlier irradiation stage [2, 4] with those from the present high-dose stage after the two irradiation

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stages. A striking feature is that doubling the accumulated damage dose does not produce a systematic displacement of the transition curves toward higher temperatures or a pronounced additional decrease in the upper-shelf energy.

For EUROFER97-3_980/780, the curves obtained after 21.6 and 45.8 dpa are almost coincident in terms of DBTT and USE (see Figure 8 a). EUROFER97-3_1100/700 shows a shift of the high-dose transition curve toward lower temperature. A similar, although smaller, tendency is observed for F82H (see Figure 8 b). The M474 curves remain essentially unchanged, whereas L664B shows a small shift toward a higher transition temperature.

The three other RAFM steels therefore show the same general feature as EUROFER97-3: the Charpy properties do not evolve monotonically toward increasing embrittlement with increasing dose at 540 °C.

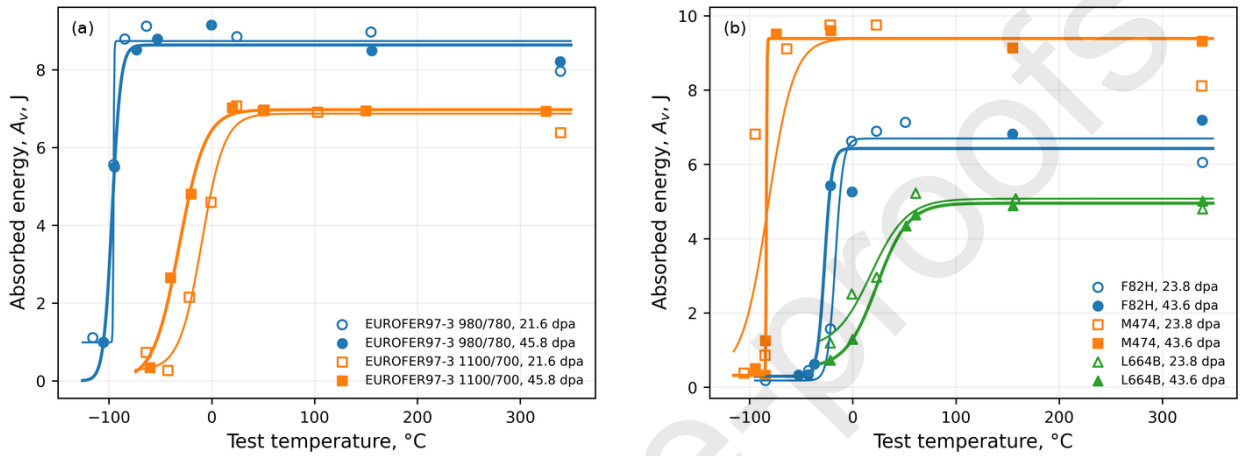


Figure 8. Impact energy, Av, as a function of test temperature after irradiation at 540 °C for (a) EUROFER97-3_980/780 and EUROFER97-3_1100/700 at 21.6 and 45.8 dpa and (b) F82H, M474, and L664B at 23.8 and 43.6 dpa. Open and filled symbols denote the lower- and higher-dose irradiation stages, respectively; solid curves show the corresponding fits to the experimental data

The quantitative changes are summarized in both Figure 9 and Table 12. For EUROFER97-3_980/780, increasing the dose from 21.6 to 45.8 dpa changes DBTT only from −95.5 to −96.9 °C (ΔDBTT=-1.4 °C) (see Figure 9 a). M474 likewise remains essentially stable, with DBTT changing from −82.1 to −83.7 °C (ΔDBTT=-1.6 °C).

More pronounced changes toward lower DBTT are observed for EUROFER97-3_1100/700 and F82H. For EUROFER97-3_1100/700, DBTT decreases from −9.7 to −31.6 °C (ΔDBTT=-21.9 °C), while for F82H it decreases from −16.9 to −27.3 °C (ΔDBTT=-10.4 °C). In contrast, L664B shows a small increase from 17.7 to 23.3 °C (ΔDBTT=+5.6 °C).

The USE evolution is even more uniform. Between the two dose levels, the changes in USE are limited to approximately −0.3 to +0.1 J for all investigated materials (see Figure 9 b). EUROFER97-3_980/780 changes from 8.7 to 8.6 J, EUROFER97-3_1100/700 from 6.9 to 7.0 J, F82H from 6.7 to 6.4 J, M474 remains at approximately 9.4 J, and L664B changes from 5.1 to 5.0 J. Thus, within the scatter inherent in Mini-Charpy testing and fitting, the upper-shelf energy can be regarded as essentially saturated after the first irradiation stage.

The absence of progressive Charpy degradation between approximately 20 and 40 dpa is consistent with the tensile results and indicates that irradiation at 540 °C does not lead to continuous accumulation of mechanically effective radiation damage. Instead, competing irradiation-induced and thermally activated processes appear to establish a dynamic microstructural evolution in which additional damage accumulation is partly or completely compensated by recovery and structural rearrangement. High-dose BOR-60 studies at lower irradiation temperatures have likewise shown that the dose dependence of hardening and DBTT can weaken or approach saturation, although the absolute response and governing balance of mechanisms are temperature dependent [15, 16].

This interpretation is particularly supported by the simultaneous stabilization of strength, tensile ductility and USE. The decrease in DBTT observed for EUROFER97-3_1100/700 and F82H may indicate that the balance between hardening and recovery changes with increasing dose. However, considering the limited number of Charpy specimens and the sensitivity of fitted DBTT to individual transition-region data points, this apparent recovery should be regarded only as a tendency of the present dataset rather than evidence for a specific microscopic mechanism. The strong sensitivity of RAFM irradiation response to temperature and

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microstructural state is well established in the literature [16,19-21].

The behavior of L664B is somewhat different: DBTT increases by about 6 °C between the two dose levels, while USE remains essentially unchanged. The magnitude of this change is small compared with the material-to-material differences in absolute DBTT and does not indicate pronounced progressive embrittlement.

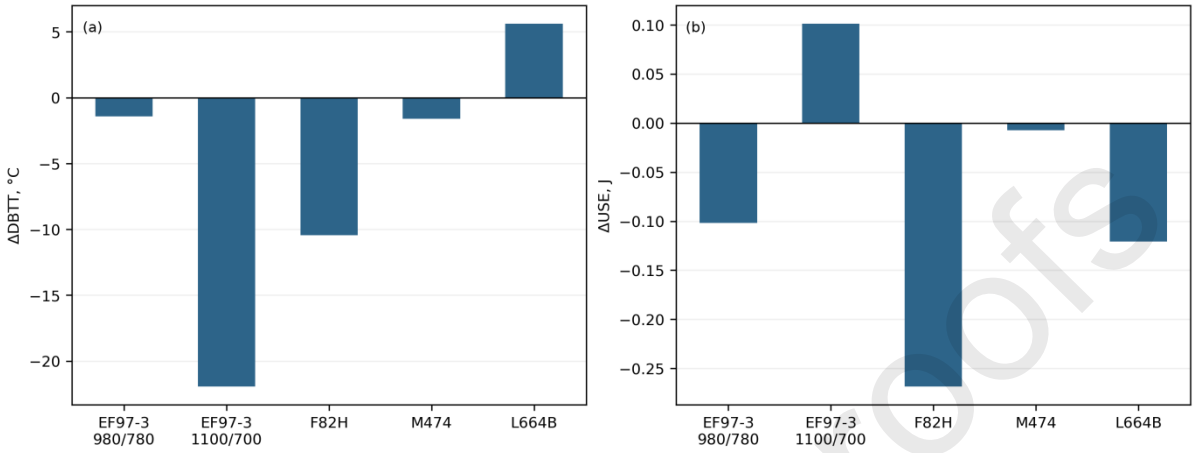


Figure 9. Comparison of (a) ΔDBTT and (b) ΔUSE for EUROFER97-3_980/780, EUROFER97-3_1100/700, F82H, M474, and L664B after irradiation at 540 °C, with the damage dose increasing from 21.6–23.8 to 43.6–45.8 dpa. Values are fitted point estimates; confidence intervals are not shown

Despite substantial differences in their absolute mechanical properties, no material exhibits an overall deterioration in both strength/ductility and Charpy properties between approximately 20 and 40 dpa. Each material also retains particular advantageous characteristics: EUROFER97-3_980/780 combines a low DBTT with relatively high ductility; EUROFER97-3_1100/700 retains the highest tensile strength and shows a decrease in DBTT at high dose; F82H exhibits a moderate decrease in DBTT with increasing dose; M474 combines a low DBTT with the highest USE and good tensile ductility; and L664B maintains high strength with only small additional changes in Charpy properties.

Table 12. Charpy impact properties of RAFM steels after irradiation at 540 °C at two damage-dose levels

Steel/Heat treatment	Dose 1, dpa	Dose 2, dpa	DBTT at Dose 1, °C	DBTT at Dose 2, °C	ΔDBTT (Dose 2-Dose 1), ºC	USE at Dose 1, J	USE at Dose 2, J	ΔUSE (Dose 2-Dose 1), J
EUROFER97-3_980/780	21.6	45.8	-95.5	-96.9	-1.4	8.7	8.6	-0.1
EUROFER97-3_1100/700	21.6	45.8	-9.7	-31.6	-21.9	6.9	7.0	0.1
F82H	23.8	43.6	-16.9	-27.3	-10.4	6.7	6.4	-0.3
M474	23.8	43.6	-82.1	-83.7	-1.6	9.4	9.4	0.0
L664B	23.8	43.6	17.7	23.3	5.6	5.1	5.0	-0.1

5. Conclusions

The tensile and Charpy impact properties of EUROFER97-3 in two heat-treatment conditions and of the RAFM steels F82H, M474, and L664B were investigated after neutron irradiation in the BOR-60 reactor at 540 °C to damage doses exceeding 40 dpa. Comparison with the previous irradiation stage at approximately 20 dpa allowed the evolution of the mechanical properties with dose to be assessed.

The main conclusions are as follows:

Tensile properties.

Increasing the damage dose from 19.2–23.8 to 41.5–43.6 dpa does not result in progressive irradiation hardening common to all investigated steels. Additional strengthening is small for EUROFER97-3_980/780, negligible for EUROFER97-3_1100/700 and L664B, and moderate for F82H and M474. No systematic reduction in tensile ductility is observed; uniform elongation generally increases, while total elongation remains at relatively high levels.

Charpy impact properties.

Increasing the dose from 21.6–23.8 to 43.6–45.8 dpa does not produce systematic additional embrittlement. DBTT remains essentially unchanged for EUROFER97-3_980/780 and M474, decreases by approximately 22 °C for EUROFER97-3_1100/700 and 10 °C for F82H, and increases by only approximately 6 °C for L664B. USE is remarkably stable for all investigated material conditions, with changes between the two dose levels not exceeding approximately 0.3 J.

General behavior.

The combined tensile and Charpy results demonstrate a tendency toward stabilization of the mechanical properties of the investigated RAFM steels during neutron irradiation at approximately 540 °C as the damage dose increases from about 20 to more than 40 dpa. The absence of monotonic hardening and embrittlement suggests that, at this irradiation temperature, the accumulation of irradiation damage competes with thermally activated recovery and microstructural rearrangement. The relative contributions of these processes depend on the initial microstructure and heat treatment of the individual steels.

Overall, the results indicate that increasing neutron damage from approximately 20 to more than 40 dpa at 540 °C does not lead to progressive degradation of the tensile and Charpy impact properties of the investigated RAFM steels.

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Highlights

- Five RAFM steel conditions were neutron irradiated at 540 °C to 41–46 dpa.
- Increasing dose above ~20 dpa causes no systematic progressive tensile hardening.
- Charpy properties show no progressive embrittlement and essentially stable USE.
- Mechanical properties tend to stabilize between ~20 and >40 dpa at 540 °C.

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