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Charpy impact properties of EUROFER97-3 after neutron irradiation at 330 °C and 540 °C to damage doses of 21–23 dpa

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ABSTRACT

The reduced activation ferritic-martensitic (RAFM) EUROFER97-3 steel of two heat treatments (EUROFER97-3_1100/700 and EUROFER97-3_980/780) after irradiation in the BOR-60 fast reactor at temperatures of 330 °C and 540 °C, with damage doses ranging from 21.6 to 22.8 dpa showed big differences in the Charpy impact properties depending on the irradiation temperature. Significant drop in the upper shelf energy (USE) and shift of the ductile–brittle transition temperature (DBTT) occurred after irradiation at 330 °C. However, irradiation at 540 °C resulted in only minor changes in the USE and DBTT compared to the unirradiated reference state. Probably, these changes are attributed of the formation of radiation-induced defects and evolution in the phase structure.

1. Introduction

EUROFER97 steel represents the outcome of extensive R&D efforts aimed at creating reduced-activation ferritic–martensitic (RAFM) alloys suitable for fusion reactor environments. Developed at KIT in Germany (formerly FZK), this material has been selected as the leading candidate for the structural components of DEMO breeding blankets [1–5]. In the present study, we focus on the third industrial batch of this alloy, designated EUROFER97-3, which was manufactured within the Test Blanket Module (TBM) program [6].

Within the broader DEMO materials development roadmap, EUROFER97-3 is scheduled to undergo a comprehensive assessment of key mechanical properties, including fracture toughness, tensile behavior, Charpy impact response, low-cycle fatigue performance, and creep resistance, – under neutron irradiation. These tests are being carried out in the BOR-60 fast reactor, which offers sufficiently high fast-neutron fluxes to reach irradiation levels of about 20 dpa for the initial DEMO blanket set and 40–50 dpa for the subsequent set within irradiation campaigns of roughly two and four years, respectively [7].

Irradiation temperatures of 325 °C and 550 °C have been selected to represent the lower and upper operational bounds for both HCPB (Helium-Cooled Pebble Bed) and WCLL (Water-Cooled Lithium-Lead) blanket concepts.

The goal of this work is to evaluate how neutron exposure to a dose of 20 ± 2 dpa at target temperatures of 325 ± 10 °C and 550 ± 20 °C affects the Charpy impact behavior of EUROFER97-3 steel.

2. Experimental

2.1. Materials, specimens, heat treatment

The EUROFER97-3 plate used in this work (dimensions: 1015 × 532 × 33.3 mm) was produced by Saarschmiede Freiformschmiede GmbH through a multistage manufacturing route consisting of:

- primary melting in a vacuum induction furnace;
- secondary melting via vacuum arc remelting;
- forging to a billet of roughly 700 × 150 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 (minimum achievable thickness ≥19 mm);
- final quality heat treatment.

Mini-Charpy impact specimens (Fig. 1) were machined from this plate together with creep [8] and tensile [9] specimens. Two sets of the impact specimens were produced, each subjected to a different heat-treatment schedule (Table 1), and all were oriented such that the

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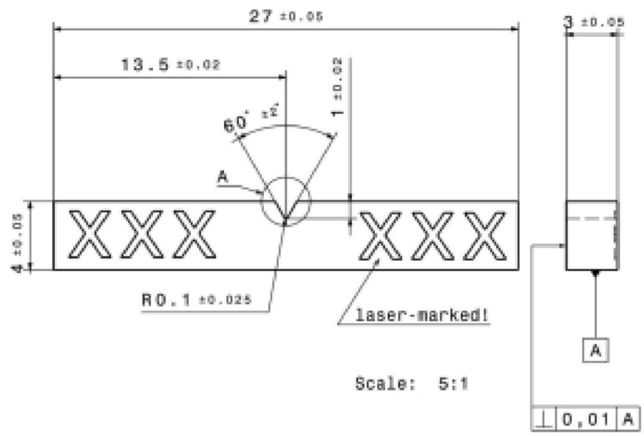

Fig. 1. Impact bending (Mini Charpy) specimen for irradiation testing in BOR-60 reactor.

Table 1
Heat treatments of the EUROFER97-3 Charpy impact specimens.

Grade	Austenitization	Quenching	Tempering	Final cooling
EUROFER97-3_1100/700	1100 °C, 0.5 h	air	700 °C, 2 h	air
EUROFEF97-3_980/780	980 °C, 0.5 h	air	780 °C, 2 h	air

Table 2
Grain size and Vickers micro-hardness under a load of 1 kg (HV1) of the EUROFER97-3 Charpy impact specimens.

Grade	Grain size, μm	Vickers micro-hardness HV1
EUROFER97-3_1100/700	16.1	313–317
EUROFEF97-3_980/780	5.2	196–204

Table 3
Chemical composition of EUROFER97-3 steel 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	0.0430 ± 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	1.00–1.20	1.152 ± 0.040

rolling direction lay perpendicular to the specimen axis.

EBSD characterization of EUROFER97-3 after the two heat treatments, performed at a magnification corresponding to a 100 μm field of view, indicates that both routes yield a tempered martensitic structure composed of lath and packet features. Nonetheless, the packet size differs appreciably: the 980/780 °C treatment results in an average prior austenite grain size of about 5.2 μm, whereas the 1100/700 °C treatment produces a substantially larger value of approximately 16.1 μm (Table 2). No pronounced crystallographic texture was detected at this scale. Hardness measurements show a similar contrast: the EUROFER97-3_980/780 material exhibits 196–204 HV1, while the EUROFER97-3_1100/700 condition shows markedly higher hardness, in the range of 313–317 HV1 (Table 2).

Table 4
Irradiation parameters for the EUROFER97-3 Charpy impact specimens.

Grade	T_{irr}, °C target/actual	F, $\times 10^{26}$ m^{-2}, E > 0.1 MeV	D, dpa
EUROFER97-3_1100/700	325/330	5.12	22.8
	550/540	4.77	21.6
EUROFER97-3_980/780	325/330	5.12	22.8
	550/540	4.77	21.6

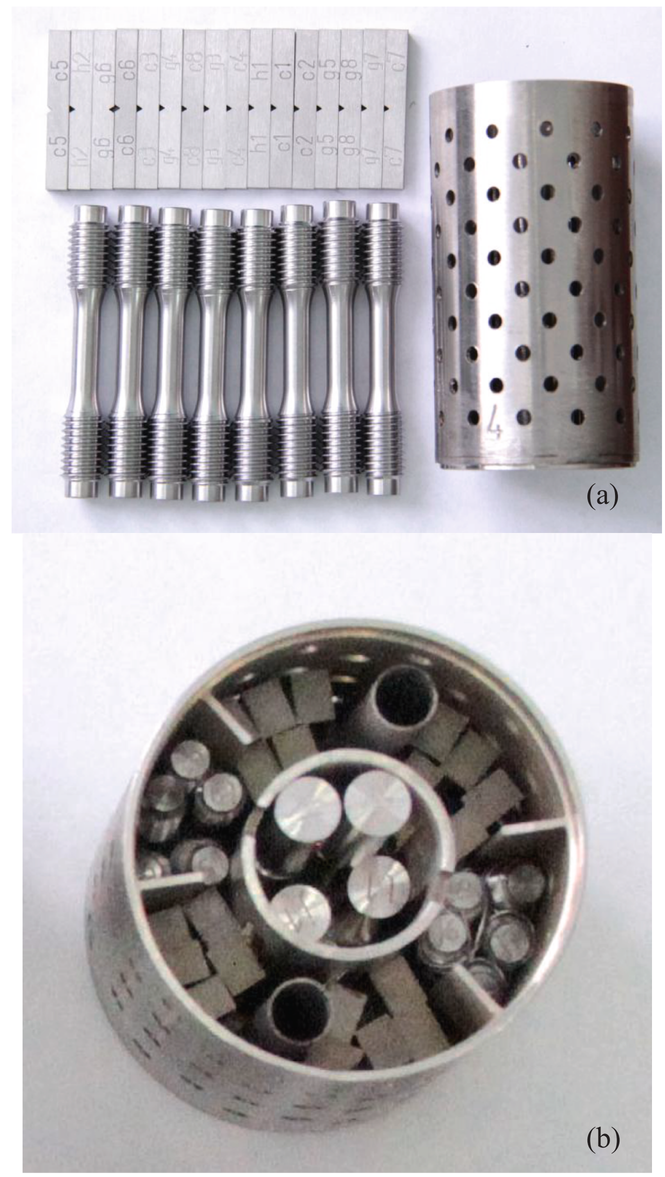

Fig. 2. Impact bending (Mini Charpy) specimens next to drum (a, upper left) and in the drum (b) of IR2 rig for irradiation testing at 540 °C in the BOR-60 reactor.

The chemical composition of EUROFER97-3 is presented in Table 3. Measurements performed at KIT (see the third column) show that the

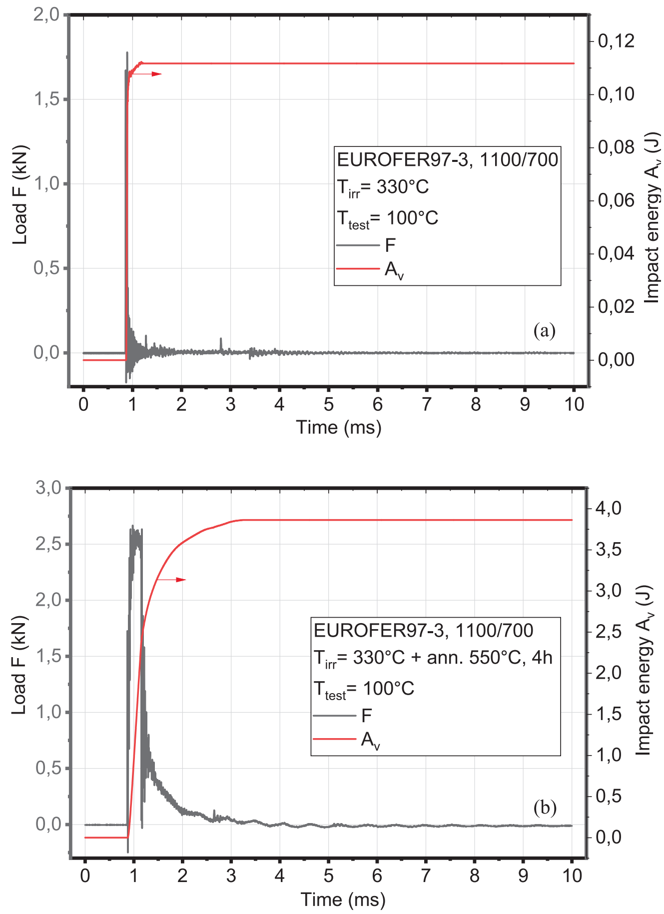

Fig. 3. Impact Charpy load-time diagram of EUROFER97-3_1100/700 after irradiation at 330 °C (a), and after irradiation at 330 °C with additional annealing at 550 °C for 4 h (b); the test temperature T_{test} = 100 °C for both conditions.

material meets the specified delivery requirements (second column in Table 3).

2.2. Irradiation

The EUROFER97-3 Charpy impact specimens were irradiated in the BOR-60 fast reactor, using the IR1a and IR2 rigs positioned in the 6th and 5th core rows, respectively, and operated with sodium coolant. The irradiation conditions for the Charpy impact specimens are summarized in Table 4.

The specimens were housed in the perforated capsules, allowing direct exposure to the circulating liquid sodium throughout irradiation (Fig. 2 a, b). The specimen irradiation temperatures were determined from the temperature of the sodium coolant flowing over them during reactor operation.

The irradiation conditions were evaluated using established data on energy deposition in the materials and on neutron flux levels within the reactor channels. The estimated accuracy of the temperature calculations is on the order of ±10 %, while neutron flux values carry an uncertainty of roughly ±20 %. The damage dose, computed for iron using the NRT (Norgett–Robinson–Torrens) methodology, was determined based on the precise axial positions of the impact bending specimens within the irradiation channels.

Both the IR1a and IR2 rigs were outfitted with temperature and neutron monitors, enabling continuous tracking of irradiation parameters. These monitors were periodically removed for examination in a hot cell, after which replacement monitors were inserted to maintain ongoing surveillance.

As summarized in Table 4, the actual irradiation temperatures and accumulated doses for the impact specimens stayed within the acceptable bounds relative to the specified target conditions.

2.3. Charpy impact testing

The Mini-Charpy impact tests were performed in a hot-cell facility using an instrumented remote Zwick 5113 impact tester. The main specifications of the Zwick 5113 system are as follows:

- support span of 22 mm for positioning the specimen during impact;
- a 15-J pendulum equipped with a 2-mm-radius instrumented striker;
- a temperature-conditioning unit capable of setting specimen temperatures between –190 and +680 °C;
- a pneumatic handling system that transfers specimens from the storage drum to the thermostat, then from the thermostat to the supports, and positions them securely for testing.

During each test, the load–time curve was recorded, and the impact energy (fracture work) was obtained from this signal. The nominal test temperature reported in the protocol accounts for the actual temperature changes experienced by the specimen during transfer from the furnace to the supports and during hammer impact. The testing procedure follows the ISO-CD14556:2000(E) standard.

Following each test, the fractured specimen was visually examined and photographed with a Logitech C920 webcam installed inside the hot cell.

3. Results

3.1. Charpy impact properties of EUROFER97-3 before and after irradiation

As an example of the Charpy impact load-time diagrams of the EUROFER97-3_1100/700 specimens, Fig. 3 shows such diagrams after irradiation at 330 °C (Fig. 3 a) and after irradiation at 330 °C plus an annealing at 550 °C for 4 h (Fig. 3 b) at the same test temperature T_{test} = 100 °C for both specimens. Fig. 4 shows an appearance of the Charpy impact specimen fragments after testing at T_{test} = 100 °C (for both conditions) after irradiation at 330 °C (Fig. 4 a) and with an additional annealing at 550 °C for 4 h (Fig. 4 b). This example illustrates the effect of short-term annealing at a comparatively higher temperature of 550 °C on the behavior of the EUROFER97-3 steel irradiated at 330 °C, which is expressed in a significant increase in the load value and, accordingly, in the impact energy too. The appearance of the fragments confirms the conclusion about improvement of the impact properties of the irradiated EUROFER97-3 steel after additional high-temperature annealing. In particular, after irradiation, the fracture surface of the irradiated specimen has the appearance of a brittle fracture, while after additional annealing, the specimen did not separate into two parts, which indicates a significant increase in the impact energy.

Fig. 5 shows the impact load-time diagrams of the EUROFER97-3_980/780 steel specimens after irradiation at 540 °C, and test temperatures T_{test} = −100 °C (Fig. 5 a) and T_{test} = 20 °C (Fig. 5 b). The testing at T_{test} = −100 °C leads to brittle fracture (Fig. 6 a), and at room temperature (20 °C), it leads to the testing without the specimen being separated into two parts (Fig. 6 b), indicating a significant increase of the impact energy.

Fig. 7 shows the impact energy A_v vs. test temperature T_{test} curves for EUROFER97-3_1100/700 (Fig. 7 a) and EUROFER97-3_980/780 (Fig. 7 b) before (reference) and after irradiation. Table 5 presents the results of processing the curves from Fig. 7 to obtain the values of upper-shelf energy (USE) and lower-shelf energy (LSE), as well as ductile–brittle temperature transition (DBTT). The curves in Fig. 7 are resulting of a sigmoid (logistic/Boltzmann) approximation/fitting of the experimental

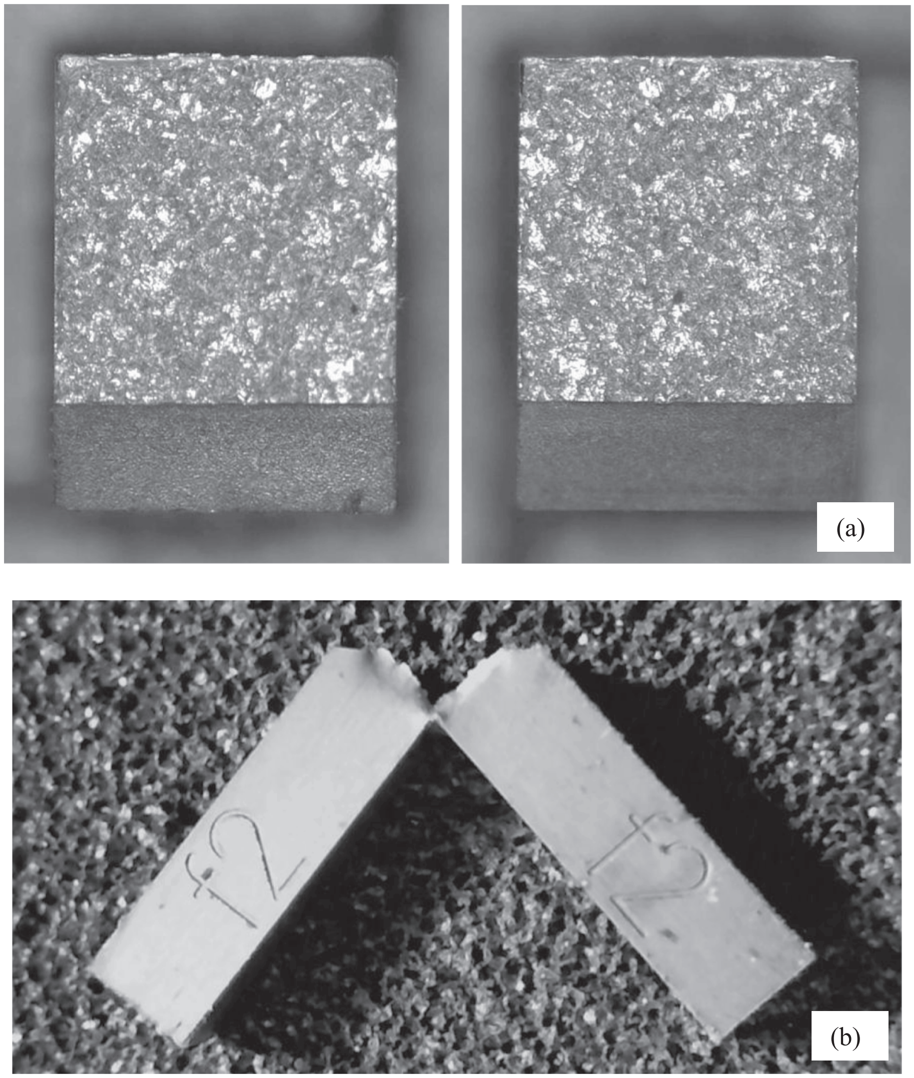

Fig. 4. Appearance of Charpy impact specimen fragments after testing at T_{test} = 100 °C of both conditions as EUROFER97-3_1100/700 irradiated at 330 °C (a), and after irradiation at 330 °C with additional annealing at 550 °C for 4 h (b).

data points obtaining finally the E_{high} asymptotic value as a USE.

In the pre-irradiation (reference) state, the two heat treatments of EUROFER97-3 studied exhibit different impact properties relative to each other. The EUROFER97-3_1100/700 steel exhibits a comparatively lower USE (8.51 vs. 10.39 J) and a significantly higher DBTT (−8.27 vs. −121.65 °C) (see Table 5).

Neutron irradiation causes degradation of Charpy impact properties, leading to a reduction in the USE and a shift in the DBTT toward higher temperatures. However, the quantitative effect of irradiation on test results depends on the heat treatment of the EUROFER97-3 steel and the irradiation temperature.

Irradiation at 330 °C causes a significant decrease in the USE and a shift in the DBTT toward higher temperatures for EUROFER97-3 of both heat treatments, but for EUROFER97-3_1100/700, the negative effect of irradiation is significantly greater compared to that for EUROFER97-3_980/780 (see Table 5). Post-irradiation annealing at 550 °C for 4 h leads to a partial recovery of the impact properties of the EUROFER97-3_1100/700 steel, i.e., the USE increases and the DBTT shifts toward lower temperatures.

Irradiation at 540 °C has a significantly lesser effect on the impact properties of the EUROFER97-3 steel. The properties after irradiation deteriorated only slightly: the USE for both heat treatments decreased by no more than 10–13 %, and the DBTT remained after irradiation in the subzero temperature range (see Table 5).

In summary, the obtained test results for EUROFER97-3 of two different heat treatments and irradiated to 20 dpa clearly show that irradiation temperature—330 °C versus 540 °C—has a fundamentally different influence on the Charpy impact properties (see Fig. 7, Table 5). At 330 °C, the Charpy impact properties degradation is much stronger. Conversely, at 540 °C, irradiation effects are minimal.

4. Discussion

The experimental Charpy impact results expand on and complement the previously published tensile test results for EUROFER97-3 steel of two heat treatments irradiated at 330 and 540 °C up to 20 dpa [9]. The published tensile data demonstrated a fundamental difference in the effect of neutron irradiation at different temperatures of 330 and 540 °C, highlighting the criticality of irradiation at comparatively lower temperature of 330 °C, where strong radiation hardening and embrittlement took place.

A limited number of Charpy impact test results for EUROFER97 after neutron irradiation at relevant temperatures and doses has been published in the literature [10–14]. The most representative is [15], in which Gaganidze presents the Charpy impact test results for RAFM steels including EUROFER97 after irradiation in the BOR-60 fast reactor at

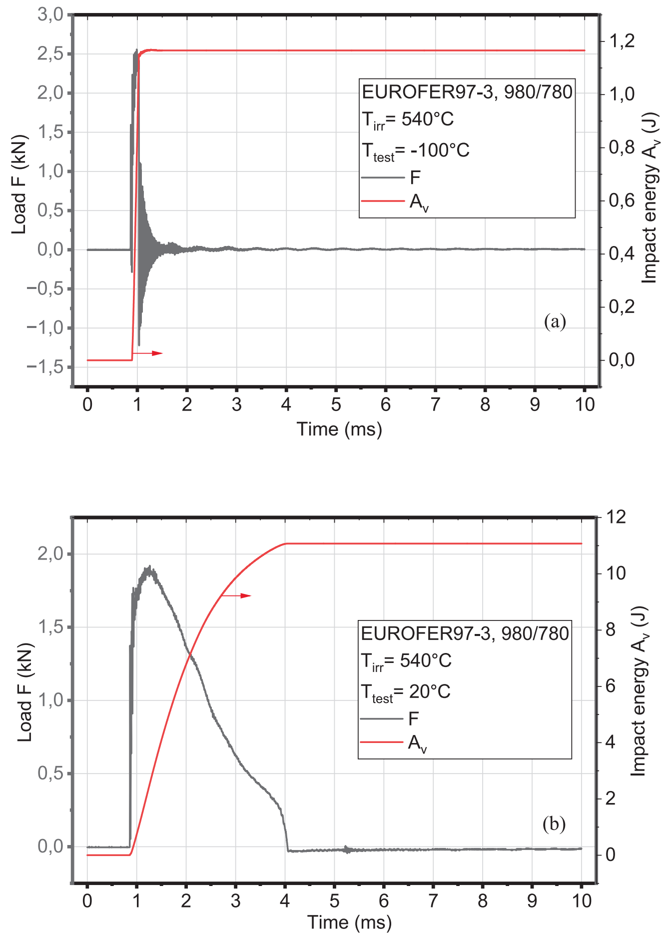

Fig. 5. Impact Charpy load-time diagram of EUROFER97-3_980/780 after irradiation at 540 °C, and test temperatures T_{test} = -100 °C (a) and T_{test} = 20 °C (b).

330–340 °C.up to 70 dpa.

Fig. 8 presents a direct comparison of the results from this study and Gaganidze's data from [15] after irradiation at 330–340 °C. This publication includes the Charpy impact results for the EUROFER97-83697 batch of two heat treatments such as 980 °C/0.5 h + 760 °C/1.5 h (980/760), and 1040 °C/0.5 h + 760 °C/1.5 h (1040/760).

Fig. 8a shows the impact results for EUROFER97 after similar austenitization temperatures (1100 vs. 1040 °C) but different quenching temperatures, which in our study were significantly lower (700 vs. 760 °C). As a result, the pre-irradiation USE values are similar for both heat treatments, while the DBTT for EUROFER97-3_1100/700 is approximately 100 °C lower than for EUROFER97-83697_1040/760. Irradiation of EUROFER97-3_1100/700 up to 21–23 dpa reveals the total degradation of the Charpy impact properties (USE ~ 2 J, DBTT ~ 170 °C), while EUROFER97-83697_1040/760 irradiated even up to factor three higher damage dose of 65–70 dpa shows much better properties (USE ~ 5 J, DBTT ~ 125 °C). Apparently, the main factor that led to the more degradation of the EUROFER97-3_1100/700 steel impact properties was the significantly lower quenching temperature (700 versus 760 °C).

Fig. 8b reflects radiation behavior of the EUROFER97 steel of different batches with practically same heat treatment (980/780 and 980/760) irradiated to doses differing of factor three. Despite the big difference in the damage doses, the USE for both batches has the same value of ~ 6 J. However, the higher dose causes a greater shift of DBTT (~150 °C versus ~ 50 °C).

Currently, EUROFER97-3_980/780 is undergoing irradiation up to damage dose of 40 dpa, with planned impact tests of irradiated Charpy specimens planned for mid-2026. According to available literature data [15], the DBTT in this case will be in the region of 50–150 °C (~100 °C).

There is a complete lack of literature data on the Charpy impact properties of the EUROFER97 steel after irradiation at 540 °C. Irradiation in the HFR of the EUROFER97_ANL batch at 400 and 450 °C up to 16.3 dpa leads to a slight shift in the DBTT and a slight decrease in the USE (see Fig. 2 from [11]). This is consistent with the results of this study, although they were obtained at a higher irradiation temperature (540 °C versus 450 °C).

A study of the fracture surface by SEM and TEM analysis of the tested Charpy impact specimens, irradiated at 330 °C and 540 °C to ~ 20 dpa, is scheduled in the first half of 2026. This will provide information to clarify the radiation-induced microstructural features of EUROFER97-3 for more understanding of the results on the Charpy impact properties from this study [16–19].

5. Conclusions

The Charpy impact properties of EUROFER97-3 steel were investigated using specimens subjected to two heat treatments (EUROFER97-3_1100/700 and EUROFER97-3_980/780) and irradiated in the BOR-60 fast reactor at target temperatures of 325 ± 10 °C and 550 ± 20 °C, corresponding to actual average temperatures of 330 °C and 540 °C, respectively. The irradiation damage doses ranged from 21.6 to 22.8 dpa.

The main established features are as follows:

- At 330 °C, irradiation causes degradation of the Charpy impact properties for both heat treatments, characterized by a pronounced decrease in USE and a significant shift of the DBTT to higher temperatures. At the same time, EUROFER97-3_980/780 exhibits a smaller degree of degradation than EUROFER97-3_1100/700. A positive effect of short-term annealing (550 °C for 4 h) on the partial recovery of the Charpy impact properties of EUROFER97-3_1100/700 irradiated at 330 °C has been confirmed.
- At 540 °C, irradiation causes only minor deterioration of the Charpy impact properties of EUROFER97-3 for both heat treatments, while preserving in the irradiated state the differences in Charpy impact properties between the two heat treatments that existed prior to irradiation.
- It was clearly demonstrated for EUROFER97-3 under both heat treatments that irradiation up to 21–23 dpa results in markedly different responses at 330 °C and 540 °C. At an irradiation temperature of 330 °C, the degradation of Charpy impact properties is much more pronounced than at 540 °C, where irradiation effects are minimal. This strong temperature dependence of the radiation response is attributed to the formation of radiation-induced defects (black dots, dislocation loops, voids) and to the evolution of the initial reference phase structure. Transmission electron microscopy (TEM) investigations of irradiated EUROFER97-3 Charpy specimen fragments are planned for 2026 and are expected to provide further insight into the microstructural processes responsible for the significant differences in radiation response between the two heat treatments, as well as for the large disparity in irradiation effects on Charpy impact properties at 330 °C and 540 °C.

CRediT authorship contribution statement

Vladimir Chakin: Writing – original draft, Supervision, Methodology, Investigation, Formal analysis, Data curation. **Carsten Bonnekoh:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Ramil Gaisin:** Writing – review & editing, Software, Investigation, Formal analysis. **Rainer Ziegler:** Writing – review & editing, Visualization, Validation, Investigation. **Michael Duerrschnabel:** Writing – review & editing, Software, Investigation, Formal analysis.

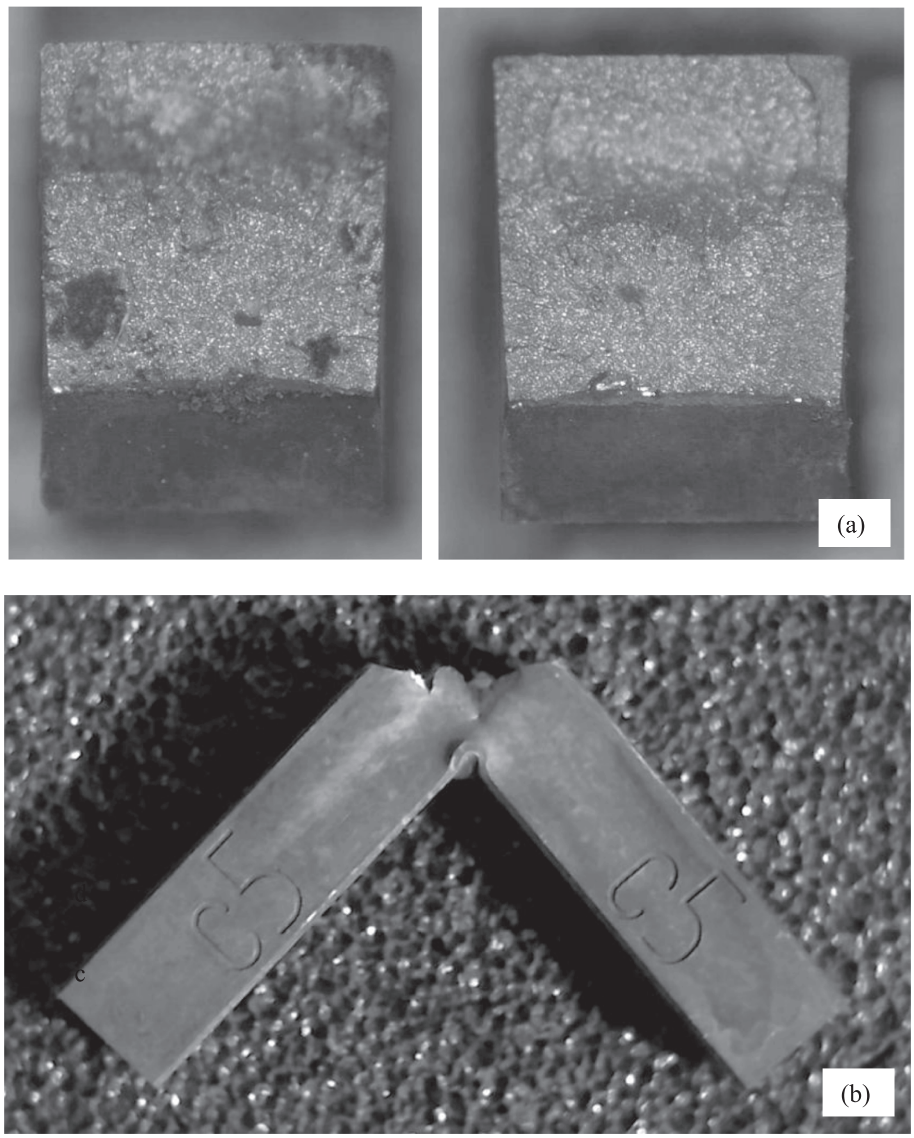

Fig. 6. Appearance of Charpy impact specimen fragments after testing of EUROFER97-3_980/780 irradiated at 540 °C and tested at T_{test} = -100 °C (a) and T_{test} = 20 °C (b).

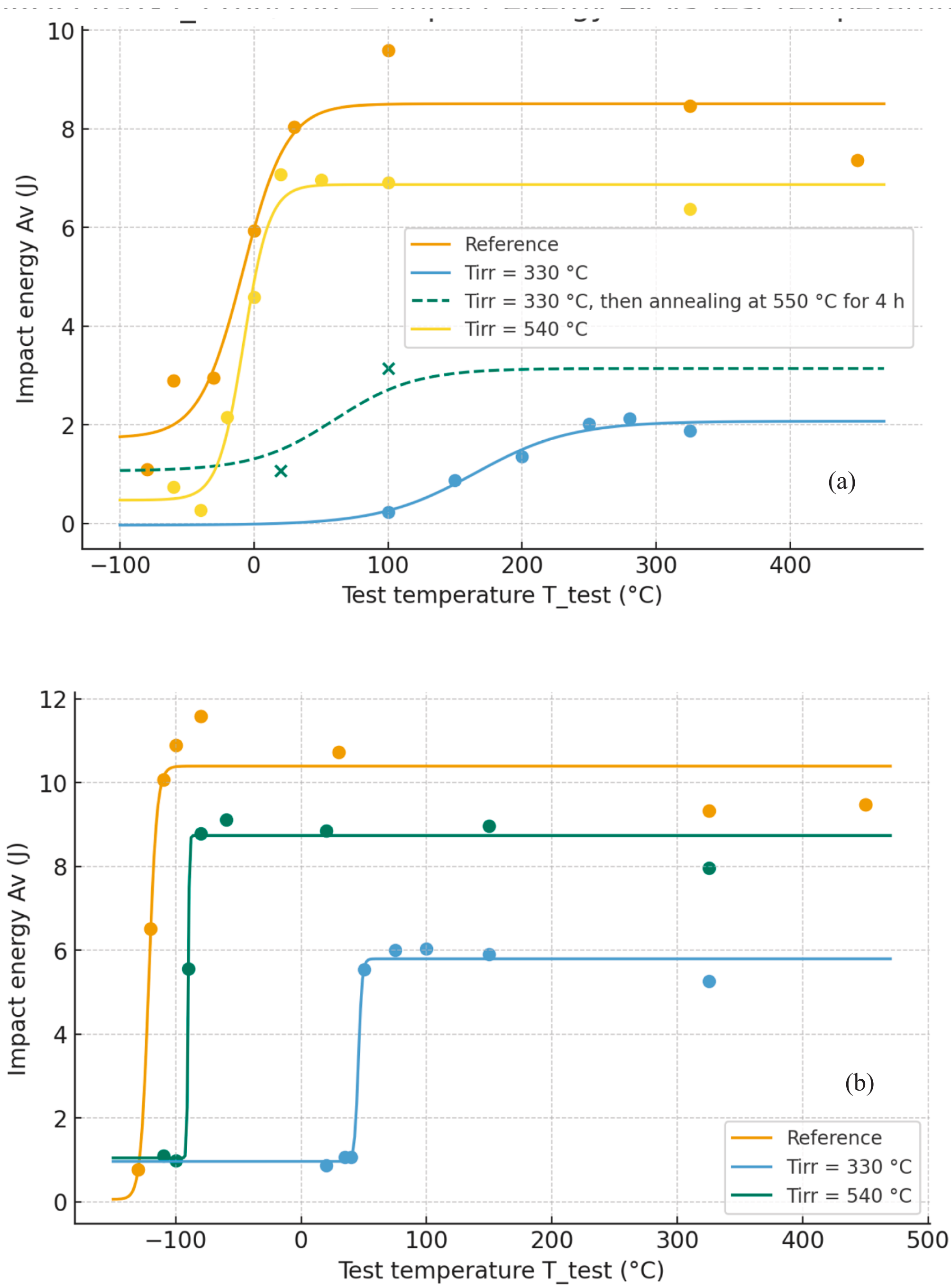

Fig. 7. Impact energy A_v – Test temperature T_{test} diagrams for EUROFER97-3_1100/700 (a) and EUROFER97-3_980/780 (b) before and after irradiation.

Table 5
Results of processing of $A_v - T_{test}$ diagrams for EUROFER97-3_1100/700 and EUROFER97-3_980/780 Charpy impact specimens before (reference) and after irradiation at T_{irr} = 330 °C and 540 °C.

Grade	State	Upper-shelf energy (USE), J	Lower shelf energy (LSE), J	DBTT, °C
EUROFER97-3_1100/700	Reference	8.51	1.73	−8.27
EUROFER97-3_1100/700	T_{irr} = 330 °C	2.07	−0.04	164.89
EUROFER97-3_1100/700, then ann. 550 °C, 4 h	T_{irr} = 330 °C	3.14	1.06	60.0
EUROFER97-3_1100/700	T_{irr} = 540 °C	6.87	0.47	−7.69
EUROFER97-3_980/780	Reference	10.39	0.06	−121.65
EUROFER97-3_980/780	T_{irr} = 330 °C	5.8	0.97	45.63
EUROFER97-3_980/780	T_{irr} = 540 °C	8.74	1.05	−90.16

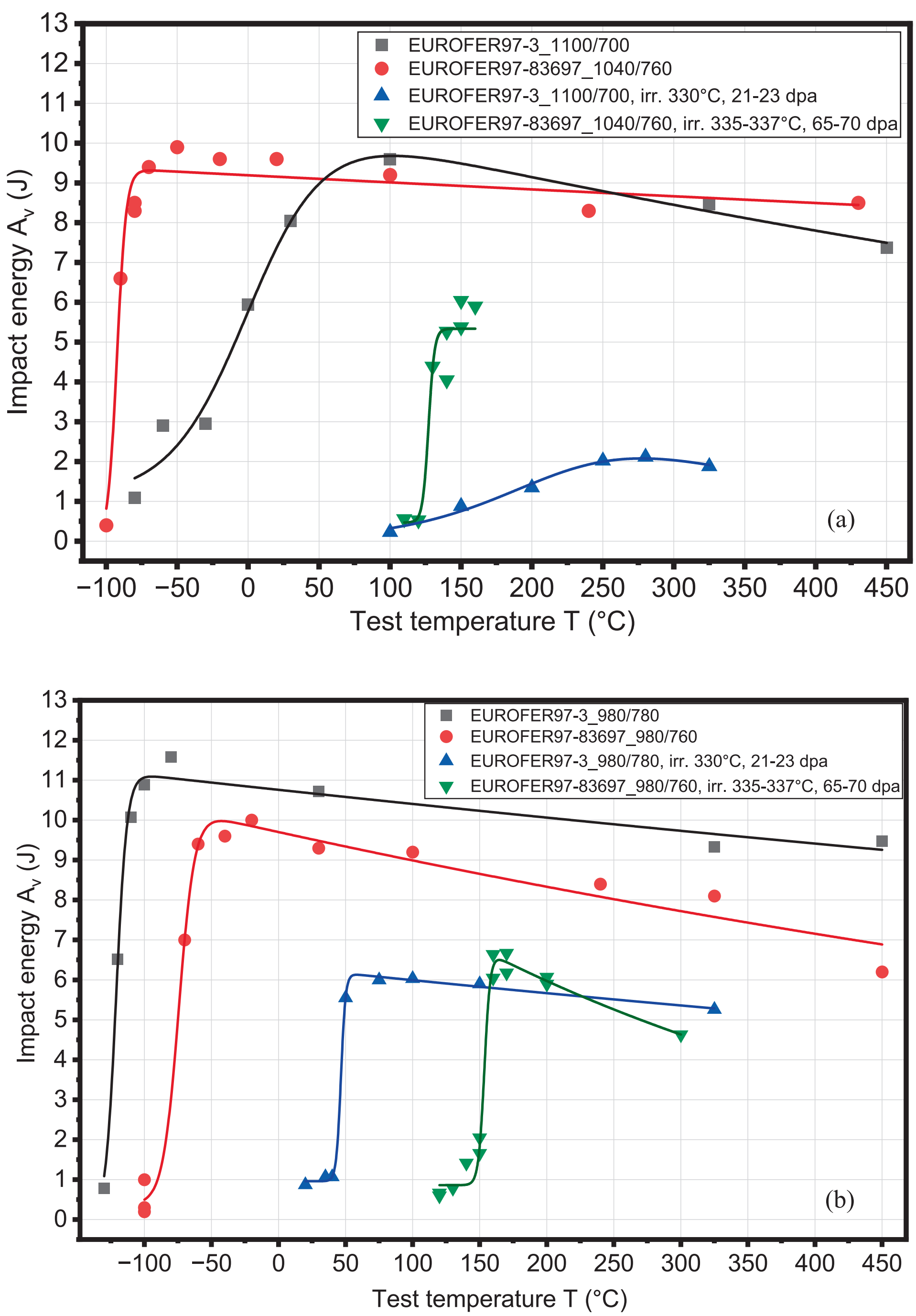

Fig. 8. Impact energy A_v – Test temperature T diagrams for EUROFER97-3_1100/700 and EUROFER97-83697_1040/760 [14] (a) as well as for EUROFER97-3_980/780 and EUROFER97-83697_980/760 [14] (b) before and after irradiation.

Michael Klimenkov: Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation. **Bronislava Gorr:** Writing – review & editing, Resources, Project administration, Funding acquisition, Conceptualization. **Michael Rieth:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

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.

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Data availability

No data was used for the research described in the article.

References

[1] M. Rieth, M. Dürrschnabel, S. Bonk, U. Jäntsch, T. Bergfeldt, J. Hoffmann, S. Antusch, E. Simondon, M. Klimenkov, C. Bonnekoh, B.-E. Ghidersa, H. Neuberger, J. Rey, C. Zeile, G. Pintsuk, G. Aiello, Technological processes for steel applications in nuclear fusion, Appl. Sci. 11 (2021) 11653, https://doi.org/10.3390/app112411653.

[2] M. Rieth, M. Dürrschnabel, S. Bonk, S. Antusch, G. Pintsuk, G. Aiello, J. Henry, Y. de Carlan, B.-E. Ghidersa, H. Neuberger, et al., Fabrication routes for advanced first wall design alternatives, Nucl. Fusion 61 (2021) 116067.

[3] G. Federici, C. Bachmann, L. Barucca, W. Biel, L. Boccaccini, R. Brown, C. Bustreo, S. Ciattaglia, F. Cismondi, M. Coleman, V. Corato, C. Day, E. Diegele, U. Fischer, T. Franke, C. Gliss, A. Ibarra, R. Kembleton, A. Loving, F. Maviglia, B. Meszaros, G. Pintsuk, N. Taylor, M.Q. Tran, C. Vorpahl, R. Wenninger, J.H. You, DEMO design activity in Europe: progress and updates, Fusion Eng. Des. 136 (2018) 729–741.

[4] G. Federici, L. Boccaccini, F. Cismondi, M. Gasparotto, Y. Poitevin, I. Ricapito, An overview of the EU breeding blanket design strategy as an integral part of the DEMO design effort, Fusion Eng. Des. 141 (2019) 30–42.

[5] Francisco A. Hernández, Pavel Pereslavtsev, Guangming Zhou, Qinlan Kang, Salvatore D'Amico, Heiko Neuberger, Lorenzo V. Boccaccini, Béla Kiss, Gábor Nádasi, Luis Maqueda, Ion Cristescu, Ivo Moscato, Italo Ricapito, Fabio Cismondi, Consolidated design of the HCPB Breeding Blanket for the pre-Conceptual Design Phase of the EU DEMO and harmonization with the ITER HCPB TBM program, Fusion Engineering and Design 157 (2020) 111614.

[6] M. Duerrschnabel, U. Jaentsch, R. Gaisin, M. Rieth, Microstructural insights into EUROFER97 batch 3 steels, Nucl. Mater. Energy 35 (2023) 101445.

[7] A.L. Izhutov, Y.M. Krasheninnikov, I.Y. Zhemkov, A.V. Varivtsev, Y. V. Naboischikov, V.S. Neustroev, V.K. Shamardin, Prolongation of the BOR-60 reactor operation, Nucl. Eng. Techn. 47 (3) (2015) 253–259.

[8] V. Chakin, C. Bonnekoh, R. Ziegler, R. Gaisin, M. Duerrschnabel, M. Klimenkov, M. Rieth, B. Gorr, M. Toloczko, Creep behavior of EUROFER97–3 steel during neutron irradiation at 325 °C and 550 °C to 7–24 dpa, Fusion Eng. Des. 215 (2025) 115014.

[9] V. Chakin, C. Bonnekoh, R. Gaisin, R. Ziegler, M. Duerrschnabel, M. Klimenkov, B. Gorr, M. Rieth, Tensile properties of EUROFER97-3 after neutron irradiation at 330 °C and 540 °C to damage doses of 19–23 dpa, Nucl. Mater. Energy 45 (2025) 102034.

[10] C. Petersen, A. Povstyanko, V. Prokhorov, A. Fedoseev, O. Makarov, B. Dafferner, Impact property degradation of ferritic/martensitic steels after the fast reactor irradiation 'ARBOR 1', J. Nucl. Mater. 367–370 (2007) 544–549.

[11] E. Gaganidze, H.-C. Schneider, B. Dafferner, J. Aktaa, Embrittlement behavior of neutron irradiated RAFM steels, J. Nucl. Mater. 367–370 (2007) 81–85.

[12] E. Gaganidze, J. Aktaa, The effects of helium on the embrittlement and hardening of boron doped EUROFER97 steels, Fusion Eng. Des. 83 (2008) 1498–1502.

[13] C. Bob van der Schaaf, Y.D. Petersen, J.W. Carlan, E. Rensman, X.A. Gaganidze, High dose, up to 80 dpa, mechanical properties of Eurofer 97, J. Nucl. Mater. 386–388 (2009) 236–240.

[14] C. Cabet, F. Dalle, E. Gaganidze, J. Henry, H. Tanigawa, Ferritic-martensitic steels for fission and fusion applications, J. Nucl. Mater. 523 (2019) 510–537.

[15] E. Gaganidze, C. Petersen, E. Materna-Morris, C. Dethloff, O.J. Weiß, J. Aktaa, A. Povstyanko, A. Fedoseev, O. Makarov, V. Prokhorov, Mechanical properties and TEM examination of RAFM steels irradiated up to 70 dpa in BOR-60, J. Nucl. Mater. 417 (2011) 93–98.

[16] M. Klimenkov, U. Jeantsch, M. Rieth, A. Moeslang, Correlation of microstructural and mechanical properties of neutron irradiated EUROFER97 steel, J. Nucl. Mater. 538 (2020) 152231.

[17] M. Klimenkov, U. Jäntsch, M. Rieth, M. Dürrschnabel, A. Möslang, H.C. Schneider, Post-irradiation microstructural examination of EUROFER-ODS steel irradiated at 300 °C and 400 °C, J. Nucl. Mater. 557 (2021) 153259.

[18] M. Klimenkov, A. Möslang, E. Materna-Morris, Helium influence on the microstructure and swelling of 9%Cr ferritic steel after neutron irradiation to 16.3 dpa, J. Nucl. Mater. 453 (2014) 54–59.

[19] M. Klimenkov, R. Lindau, E. Materna-Morris, A. Möslang, TEM characterization of precipitates in EUROFER 97, Prog. Nucl. Energy 57 (2012) 8–13.