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The ARBOR irradiation project

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Abstract

The irradiation project 'ARBOR', for 'Associated Reactor Irradiation in BOR 60', includes 150 mini-tensile/low cycle fatigue specimens and 150 mini-Charpy (KLST) specimens of nine different RAFM steels. Specimens began irradiation on 22 November 2000 in an specially designed irradiation rig in BOR 60, in a fast neutron flux (>0.1 MeV) of 1.8×10^{15} n/cm^2 s and with direct sodium cooling at a temperature less than 340 °C. Tensile, low cycle fatigue and Charpy specimens of the following materials are included: EUROFER 97, F82H mod., OPTIFER IVc, EUROFER 97 with different boron contents, ODS-EUROFER 97, as well as EUROFER 97 electron-beam welded and reference bulk material, from NRG, Petten.

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1. Introduction

In an energy generating fusion reactor, structural materials will be exposed to very high levels of irradiation damage of about 100 dpa. A simulation facility – like IFMIF – is not available in the nearer future to study materials behavior under fusion relevant irradiation conditions, e.g. specific He/dpa-ratio. Therefore these irradiation damage conditions can be realised in fast reactors only. Due to the fact that fast reactor irradiation facilities in Europe are not available anymore, a cooperation between Forschungszentrum Karlsruhe (FZK) and State Scientific Centre of Russian Federation Research Institute of Atomic Reactors (SSC RF RIAR) has been implemented. The irradiation project 'Associated Reactor Irradiation in BOR 60' is named 'ARBOR' (Latin for tree).

2. Experimental

2.1. The reactor

In December 1969 the BOR 60 experimental fast reactor started operation. Initially designed for solving physical and technical problems of fast power reactors with sodium coolant, it is nowadays also widely used as an irradiation facility for materials science purposes. With a reactor core dimension of 450 mm height and 550 mm in equivalent diameter, different irradiation positions are available. The cell D-23 has been selected, because in this position a direct temperature measurement by thermocouple during irradiation is possible.

2.2. The irradiation assembly

The design of the ARBOR irradiation device is shown in Fig. 1 (outer hexagon size, 45 mm, and specimen capsule diameter, 39 mm), and it was based on a previously used design with heat insulation against the surrounding fuel assemblies to provide relatively low irradiation temperatures. The irradiation device is

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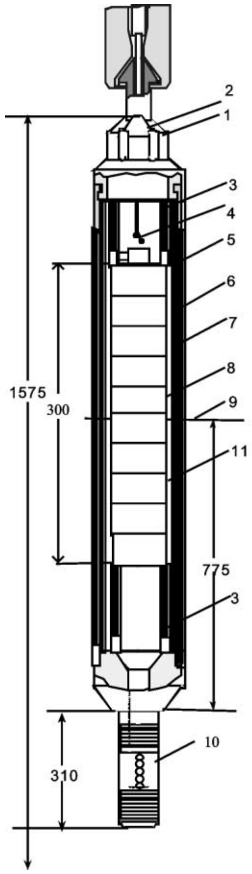

1- thermometric probe;
2- detachable head;
3- spacer tubes;
4- probe thermocouples;
5- wrapper;
6- gas gap;
7- internal tube;
8- ampoule assembly;
9- core center;
10- tail;
11- annular gap

Fig. 1. Dismountable assembly with a thermocouple.

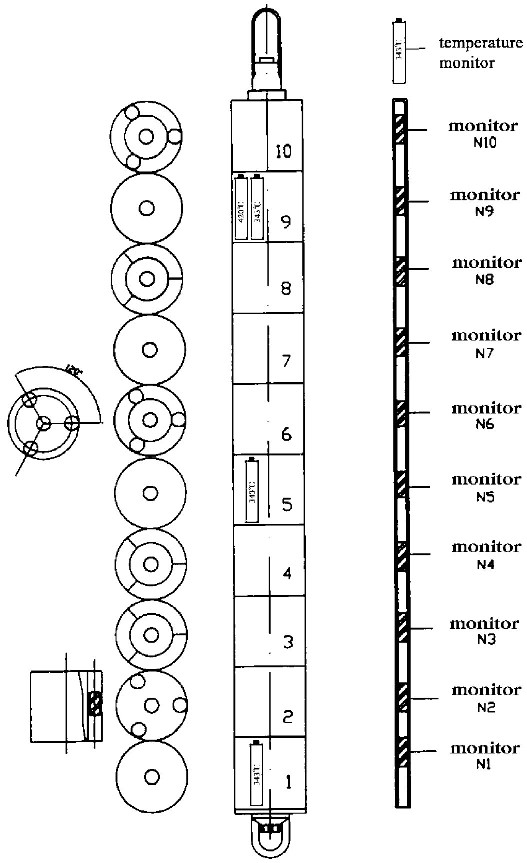

Fig. 2. Scheme of the neutron and temperature monitors location in the suspensor.

heated by the coolant from the reactor high-pressure chamber, which allows a sufficiently large coolant flow rate (of the order of 7 m^3/h) and a relatively low gamma heating rate of approximately 5 W/g (i.e. an increase of about 10–15 °C over the length of the capsule).

2.3. Dosimetry

The irradiation rig is instrumented with neutron monitors. As indicated schematically in Fig. 2, they are arranged in the central tube and on three of ten levels of specimen positions as well as with three temperature detectors also on three of ten levels.

During special reactor spectrometry experiments a large number of different material foils (about 50) were irradiated, their activity was measured and the spectrum was unfolded by using the MIXER computer code [1].

The calculation of the damage dose values for ferritic steel specimens was conducted using the SPECTER code [2]. In this case a neutron energy spectrum in cell D-23 was used that had been measured in previously performed dosimetry experiments and normalised for measured neutron fluence values with energies higher than 3, 4.6 and 7 MeV.

Metal foils with 0.1 mm thickness were used for the neutron monitors. They were cut into discs having 1.0 mm diameter. All detectors were washed in a weak solution of nitric acid, in alcohol and then they were weighed with a 'Sartorius' balance. The monitor sets were placed into labelled quartz ampoules having 3 mm diameter and 13 mm height. After irradiation the absolute measurement of γ-ray activity will be performed.

During materials science experiments only a few different foil materials (usually natural iron, niobium and titanium as well as of enriched copper: ^{63}Cu – 99.6%) are irradiated and measured. The damage dose calculation results for steel EUROFER 97 are given in Table 1, where these three normalisations and also average damage dose values for normalizations were listed. In Fig. 3, the average damage dose is plotted versus core level. The damage dose values of other types of ferritic steels under irradiation differ from those given in Table 1 by less than 0.5% [3,4]. There is a difference in the uncertainty estimations of each dosimetry result, but the

Table 1
Calculation results of damage dose for steel EUROFER 97

Level	Distance from the core central plane (mm)	Damage dose (dpa)			
		Normalization for fluence above 3 MeV	Normalization for fluence above 4.6 MeV	Normalization for fluence above 7 MeV	Average value
1	−113	3.37	3.75	3.37	3.50
2	−89	3.59	3.99	3.66	3.74
3	−59	3.70	4.08	3.77	3.85
4	−29	3.81	4.06	3.74	3.87
5	1	3.74	3.92	3.99	3.88
6	31	3.69	3.96	3.85	3.83
7	61	3.65	3.76	3.74	3.72
8	91	3.32	3.48	3.40	3.40
9	121	3.09	3.36	3.15	3.20
10	151	2.77	2.94	2.95	2.89

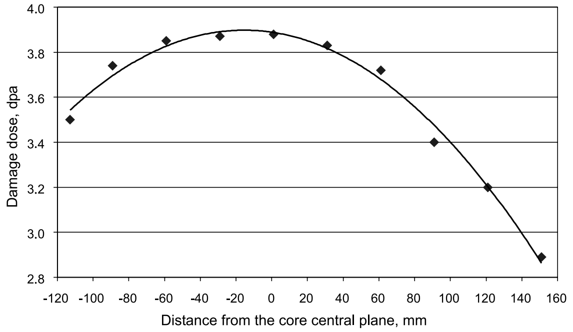

Fig. 3. The damage dose distribution for steel EUROFER 97 along the core plane.

simple averaging method is sufficient to estimate the damage dose. It was done because both the dosimetry results and the uncertainty estimations for different neutron energy ranges are close enough. Using the most accurate weights for averaging one could obtain a different value of 1–3%, but it is not better then the result of simple averaging.

2.4. The irradiated materials

Small size cylindrical specimen for tensile and low cycle fatigue testing and the KLST specimen for Charpy testing were utilised to investigate the properties after irradiation of the materials shown in Table 2 together with their heat treatment and chemical composition. The ARBOR irradiation rig includes 150 mini-tensile/low cycle fatigue specimens and 150 mini-Charpy (KLST) specimens of the nine different RAFM steels.

The European RAF/M heat EUROFER 97 is included in two heat-treated conditions. EUROF 1: EUROFER 97 (as received: 980 °C 31 min/air cooled + 760 °C 90 min/air cooled), EUROF 2: EUROFER 97 (1040 °C 31 min/air cooled + 760 °C 90 min/air cooled). EUROF 1 is optimised for good fatigue resistance and EUROF 2 for good Charpy ductile to brittle behavior. The Japanese RAF/M steel F82H mod. is implemented as the international reference steel: F82H mod. (as received: 1040 °C 38 min/air cooled + 750 °C 2 h/air cooled). The German development OPTIFER IVc (OPT IVc: 950 °C 30 min/air cooled + 750 °C 2 h/air cooled) is included as reference material to be compared to data from the HFR-irradiation. The following three materials ADS 2, ADS 3 and ADS 4, based on EUROFER 97, are experimental heats to study the influence of He on RAF/M-steels. ADS 2 is an EUROFER 97-steel with 82 wppm nat. B (1040 °C 31 min/air cooled + 760 °C 90 min/air cooled), ADS 3 an EUROFER 97-steel with 83 wppm B10 (1040 °C 31 min/air cooled + 760 °C 90 min/air cooled) and ADS 4 an EUROFER 97-steel with 1160 wppm B10 (1040 °C 31 min/air cooled + 760 °C 90 min/air cooled).

An additional feature of this ARBOR irradiation is the implementation of specimens of mechanically alloyed EUROFER 97 with 0.5% Y_2O_3 as the recent development of higher heat resistant RAF/M-steels. The specimen denotation is EURODShip: as received: 980 °C 31 min/air cooled + 760 °C 90 min/air cooled. The NRG, Petten, contribution covers technological questions with a British Steel batch of EUROFER 97, called BS-EUROF: as received: 1050 °C 60 min/air cooled + 760 °C 120 min/air cooled. In addition, the reference material for electron beam welded EUROFER 97, called EUROF-EB: as received: 980 °C 31 min/air cooled + 760 °C 90 min/air cooled, then EB welded with a post weld heat treatment at 730 °C 120 min/air cooled.

Based on the knowledge gained from earlier fatigue experiments a tensile/low cycle fatigue specimen geometry (Fig. 4) has been developed and optimised by finite element calculations using different material models. Special emphasis has been put on the radius of curvature

Table 2
Chemical composition of irridiated materials (wt%)

Material	Heat	C	Si	Mn	P	S	Cr	Mo	Ni	Al	B	Cu	N	Nb	Ti	V	W	Ta
EUROF 1	E83697	0.12	0.06	0.47	<0.005	0.004	8.93	0.0015	0.022	0.008	<0.001	0. 0036	0.018	0.0022	0.009	0.2	1.07	0.14
EUROF 2	E83697	0.12	0.06	0.47	<0.005	0.004	8.93	0.0015	0.022	0.008	<0.001	0.0036	0.018	0.0022	0.009	0.2	1.07	0.14
F82H mod.	9741	0.089	0.11	0.161	0.002	0.002	8.16	0.0018	0.0192	0.023	<0.0002	0.0055	0.0065	0.0001	0.0016	0.16	2.17	0.02
OPT IVc	986779	0.12	0.022	0.54	0.004	0.003	9.35	<0.002	0.0073	<0.0005	<0.004	0.0019	0.05	<0.0006	<0.0004	0.26	1.03	0.07
ADS 2 = EUROF1 + 82 wppm B	806	0.109	0.02	0.602	0.0035	0.003	9.31	0.002	0.005	0.001	0.0082	0.005	0.021	0.005	0.001	0.19	1.27	0.055
ADS 3 = EUROF1 + 83 wppm B	826	0.095	0.031	0.395	0.0024	0.003	8.8	0.046	0.008	0.004	0.0083	0.006	0.028	0.005	0.001	0.193	1.125	0.088
ADS 4 = EUROF1 +1160 wppm B	825	0.1	0.03	0.38	0.001	0.0025	9.0	0.028	0.006	0.004	0.112	0.005	0.0255	0.002	0.001	0.197	1.06	0.08
EUROD-Ship = EUROF1 + 0.5% Y_2O_3	HXN 958/3	0.11	0.08	0.37	0.007	0.004	8.94	0.007	0.03	0.01	<0.001	0.018	0.027	0.001	0.006	0.19	1.07	0.87
BS-EUROF	VS3102	0.094	0.05	0.42	<0.005	0.005	9.03	<0.02	<0.02	0.009	<0.001	<0.02	0.027	<0.02	<0.02	0.19	1.14	0.08
EUROF-EB = EUROF 1 EB welded	E83697	0.12	0.06	0.47	<0.005	0.004	8.93	0.0015	0.022	0.008	<0.001	0.0036	0.018	0.0022	0.009	0.2	1.07	0.14

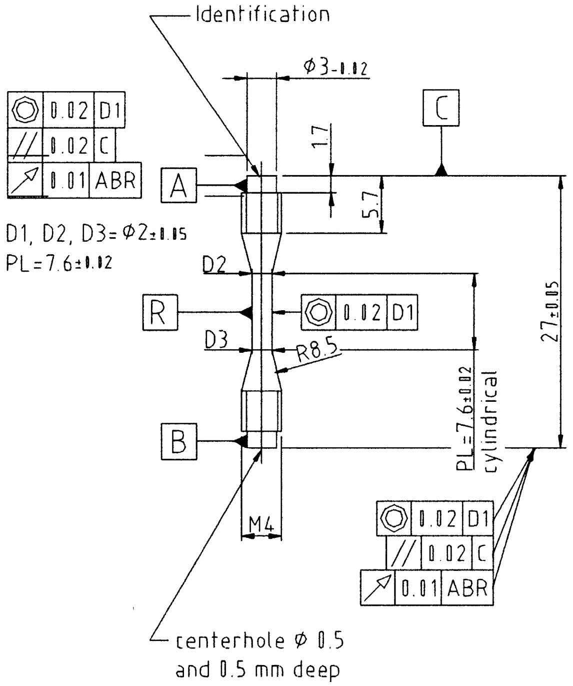

Fig. 4. Miniaturised tensile/low cycle fatigue specimen.

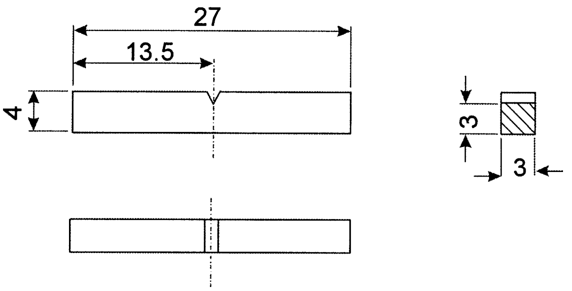

Fig. 5. KLST Charpy specimen.

at the end of the gauge length to achieve throughout the gauge volume homogeneous stress–strain fields under uniaxial push–pull fatigue testing conditions [5]. The KLST miniCharpy specimen is depicted in Fig. 5.

3. Status

Specimens have been are irradiated since 22 November 2000 in a especially designed irradiation device of BOR 60, in a fast neutron flux (>0.1 MeV) of 1.8×10^{15} n/cm^2 s and with direct sodium cooling at a temperature less than 340 °C in position D-23.

Further irradiation is planned to a dose of 30 dpa in an identical position of the 5th row of BOR 60 core.

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