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Postirradiation thermocyclic loading of ferritic–martensitic structural materials

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Abstract

Thermonuclear fusion reactors of the Tokamak-type will be unique power engineering plants to operate in thermocyclic mode only. Ferritic–martensitic stainless steels are prime candidate structural materials for test blankets of the ITER fusion reactor. Beyond the radiation damage, thermomechanical cyclic loading is considered as the most detrimental lifetime limiting phenomenon for the above structure. With a Russian and a German facility for thermal fatigue testing of neutron irradiated materials a cooperation has been undertaken. Ampule devices to irradiate specimens for postirradiation thermal fatigue tests have been developed by the Russian partner. The irradiation of these ampule devices loaded with specimens of ferritic–martensitic steels, like the European MANET-II, the Russian 05K12N2M and the Japanese Low Activation Material F82H-mod, in a WWR-M-type reactor just started. A description of the irradiation facility, the qualification of the ampule device and the modification of the German thermal fatigue facility will be presented. © 1999 Elsevier Science B.V. All rights reserved.

1. Introduction

Thermonuclear fusion reactors of the Tokamak-type will be unique power engineering plants to operate in thermocyclic mode only. Ferritic–martensitic stainless steels are prime candidate structural materials for test blankets of the ITER fusion reactor. Beyond the radiation damage, thermomechanical cyclic loading is considered as the most detrimental lifetime limiting phenomenon for the above structure.

Presently, material lifetime calculations are carried out from the point of view of their cyclic durability. For this purpose standard methods to calculate cyclic stresses, strains, time to crack initiation and its propagation are being used. However, beside isothermal fatigue data, typical data for fusion reactor materials from much more complicated loadings, first of all from thermal fatigue, are of interest for designers.

As irradiation facility the WWR-M-type reactor in Petersburg Nuclear Physics Institute (PNPI) with vacuum temperature control is available. An inside view of the reactor hall is shown in Fig. 1.

The objective of the present work is an elaboration of a technique for postirradiation thermal fatigue testing of neutron irradiated materials. Ampule devices with German type specimens had been qualified during an experimental irradiation in respect to temperature distribution, maintenance of constant irradiation-temperature of about 300°C and neutron monitoring.

2. Experimental details

Two types of postirradiation test facilities are or will be available. A Russian thermal fatigue facility and a modified German thermal fatigue facility:

The Russian facility for testing of neutron irradiated specimens was brought into service 10 years ago. A detailed description of this facility and experimental results of different materials had been presented in several papers [1–4]. This facility allows us to test specimens of any shape. Thermocyclic loading is realized by the heating of the specimens in an electrofurnace under air atmosphere up to 300–500°C and following cooling in

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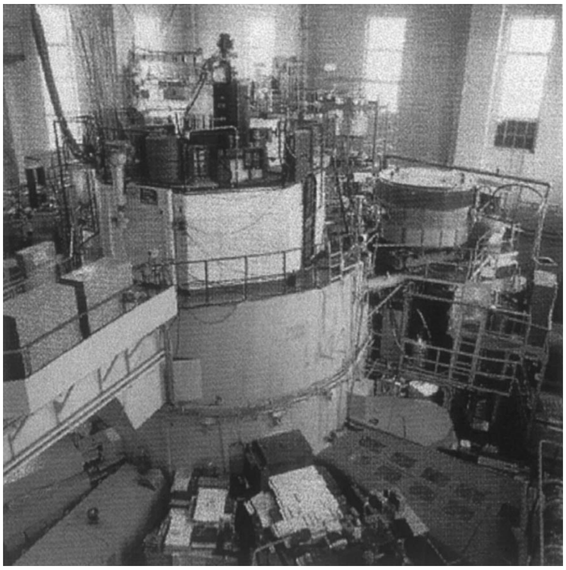

Fig. 1. Inside view of the WWR-M-reactor hall at Petersburg Nuclear Physics Institute (PNPI).

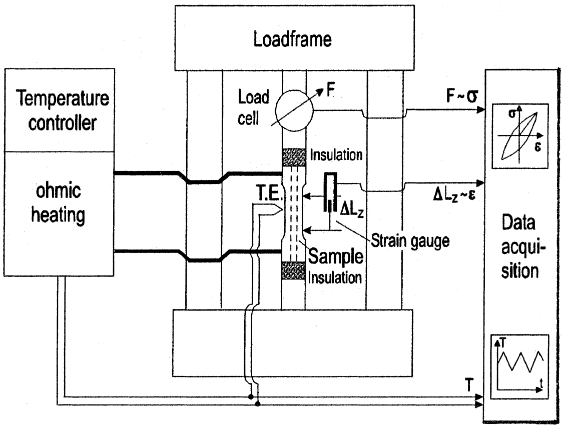

Fig. 2. Scheme of the German Thermal Cycling Fatigue facility.

air atmosphere or in distilled water or any corrosive environment. By this means, the facility makes it possible to investigate corrosive thermal fatigue of irradiated materials. In addition, using smooth cylindrical specimens with 5 mm diameter and 10 mm length it allows us to investigate the influence of thermocycling on basic mechanical properties, like strain and stress. Thermal fatigue and failure of irradiated materials in respect to fracture behavior was tested on two different cylindrical specimens of diameter × length (6×30 mm^2 and 8×30 mm^2) with longitudinal notches having a depth 0.5 and 1.5 mm and for radii around the circumference of 0.1, 0.25, 0.5 and 1.0 mm. Thermal stresses and strains had been calculated by analytical and approximate methods and by the method of finite elements [5].

The German Thermo-Cycling Fatigue (TCF) facility, schematically shown in Fig. 2, consists of a stiff load frame for mechanical clamping of the sample, which is directly heated by the digitally controlled ohmic heating device. The temperature is controlled by a pressed-on thermocouple shielded by a round Niobium plate, worked out to fit into the shape of the samples radius. Load is measured by a load cell between the frame and the lower pull rod. The optical strain measurement device was modified to be attached in the 10 mm long cylindrical gauge length of the specimens with 77 mm length and 8.8 mm diameter with a wall thickness of 0.4 mm. Variable strain rates are applied at TCF test mode, due to the constant heating rate of 5.8 K/s and variable temperature changes.

In respect with extensometry a TCF test includes complications to strain measurement not normally encountered with isothermal LCF tests. Since both temperature and mechanical strain cycling are taking place, mechanical strain is available only after subtraction of the thermal strain from the net strain.

Neutron irradiation of Russian type cylindrical specimens with notches made from a Russian ferritic–martensitic steel 05K12N2M (Fe–05C–12Cr–2Ni–Mo) and the European ferritic–martensitic reference steel MANET II (10.3Cr–0.65Ni) to be thermal cyclically tested into the Russian postirradiation thermal fatigue test facility has been performed in the WWR-M-type reactor of PNPI with fluences of 1×10^{25} n/m^2 at a temperature of about 300°C. The irradiation procedure of those specimens had been reported with other materials several times [1–4].

The ampule with thin-walled tube specimens for the German thermal fatigue facility has been developed, manufactured and assembled for an experimental irradiation to clear up the irradiation temperature conditions. A drawing of the ampule is presented in Fig. 3. The ampule assembly contains five tube specimens. Cylindrical bushes made of ferritic–martensitic steel are compacted inside two of five specimens, the other three specimens have no bushes inside. In the experimental ampule device two thermocouples are spot welded to each specimen: One, onto one end of the cylindrical gauge length of the specimen, the other, onto the specimens head. Though, in the operating ampules five thermocouples will be used, which will be welded onto the specimens heads only.

Specimens with thermocouples are placed in tightly fitting aluminium detachable cassettes, consisting of five parts. On the head of each specimen a washer is screwed, which is fixed by welding to the specimen. Then these specimens together with the cassettes are placed inside an aluminium tube and the thermocouples are led outside through especially made grooves. Neutron monitors are placed in the center and in both ends of the ampule

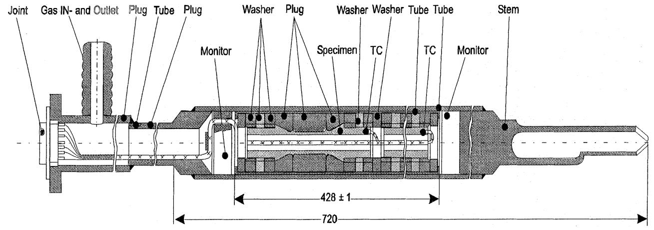

Fig. 3. Drawing of the ampule to irradiate thin walled tube specimens of German type.

for detection of the neutron fluence. The whole construction is placed inside the outer aluminium ampule without a gap between the wall of the ampule and the cassettes-tube containing the specimens. And finally, the whole assembly is welded under argon atmosphere in order to prevent primary circuit water penetration inside the ampule. The experimental ampule has been loaded into the reactor according to Fig. 4 and irradiated at the edge of WWR-M-type reactor core in PNPI inside the channel with vacuum temperature control at a flux of about 3×10^{13} n/cm^2 s. The vertical cross-section of the PNPI-WWR-M-reactor and the scheme of the gas–vacuum system to control specimens temperature is presented in Fig. 5.

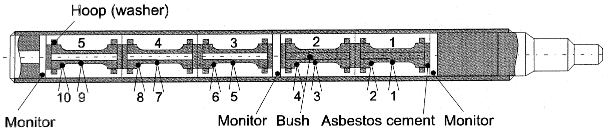

Fig. 4. Scheme of the loading plan of one of the two ampules with German tube specimens of ferritic–martensitic steels. (1) Amount of cassettes: 5, (2) Marking of cassettes: 1,2,3,4,5, (3) Material of cassettes: Aluminum, (4) Type and amount of specimens: German Type, 5; (5) Material of specimens: MANET II; 05K12H2M; (6) Marking of specimens: Number 2,3,4 (MANET II); Number 1,5 (05K12H2M); (7) Weight of specimens: MANET II: 153.6 g; 05K12H2M: 102.4 g.

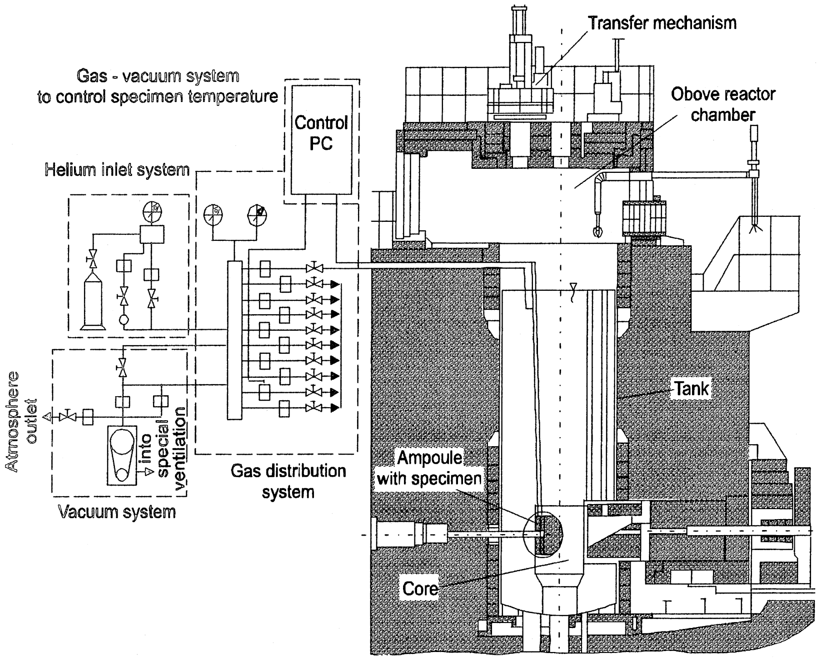

Fig. 5. Vertical cross section of the PNPI-WWR-M-reactor with the gas–vacuum system to control specimen temperature.

3. Results

The experimental determination of temperature-distributions of German tube specimens in the process of irradiation are shown in Fig. 6. It is evident from the figure that the optimum irradiation temperature equal to 300°C is reached at a vacuum of about 0.1 Pa. The most uniform temperature distribution over the specimens into the ampule takes place in specimens with bushes. On the basis of the experience of the experimental irradiation two ampules with German tube specimens of ferritic–martensitic steels (four specimens of MANET II, three specimens of 05K12N2M and three specimens of F82H mod) have been manufactured.

Besides that, cassettes with Russian type cylindrical specimens of these ferritic–martensitic steels have been placed inside two ampules. These ampules have been assembled and implemented into the reactor core to be irradiated up to a fluence of about 1×10^{24} n/m^2 at a temperature of 300°C.

Up to now two cylindrical specimens of 05K12N2M are under thermal cycling examination: One unirradiated specimen, as cold reference, and one specimen after irradiation with a fluence of 1×10^{25} n/m^2 at $T = 300$°C. Total strain ranges of 0.28% and number of cycles $N = 6500$ are reached up to now, but these specimens are not yet destroyed.

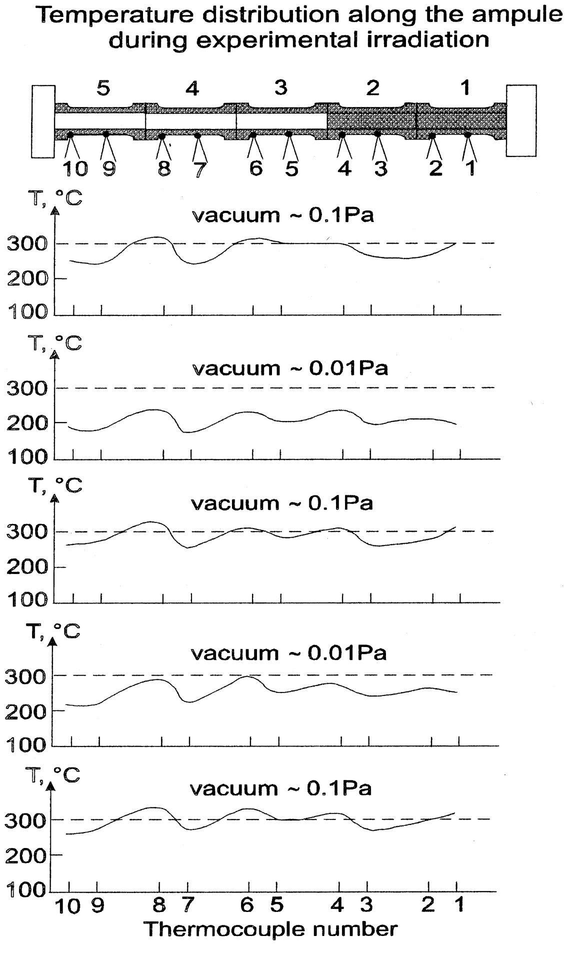

Fig. 6. Temperature distribution along the ampule during experimental irradiation for two vacuum conditions.

4. Conclusion

Ampule devices to irradiate specimens for postirradiation thermal fatigue tests have been developed and qualified by the Central Research Institute of Structural Materials, St. Petersburg. The irradiation of these ampule devices loaded with specimens of ferritic–martensitic steels, like the European MANET-II, the Russian 05K12N2M and the Japanese Low Activation Material F82H-mod, in a WWR-M-type reactor just started.

With an existing Russian and a modified German facility for thermal fatigue testing postirradiation thermal fatigue experiments will be performed in the hot cells of the Central Research Institute of Structural Materials, St. Petersburg.

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References

[1] L.A. Belyaeva, V.A. Gosudarencova, V.D. Yaroshevich, Shipconstr. Ind. Ser. Metall. 3 (1986) 38.

[2] L.A. Belyaeva, I.V. Gorynin, O.A. Kozhevnikov, V.D. Yaroshevich, Phys. Met. Phys. Metall. 1 (1990) 189.

[3] V.F. Vinokurov, I.A. Murtazin, N.B. Odintsov, L.I. Parshukov, V.V. Rybin, E.P. Shibanov, L.A. Belyaeva, Abstracts: Part 1. All-Union Conf. Irrad. Eff. on Mater. for Fusion Reactors, Leningrad, 1990, p. 81.

[4] V. V Rybin, V.F. Vinokurov, N.B. Odintsov, L.A. Belyaeva, L.G. Fedosova, J. Nucl. Mater. 191–194 (1992) 795.

[5] L.A. Belyaeva, V.F. Vinokurov, I.A. Kuzmina, E.V. Nesterova, N.B. Odintsov, V.V. Rybin, At. Energ. 74 (2) (1993) 117.