Development of a Low Temperature Irradiation Capsule for Research Reactor Materials

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ABSTRACT

A new capsule design was prepared and tested at HANARO for a neutron irradiation of core materials of research reactors as a part of the research reactor development project. Irradiation testing of the materials including graphite, beryllium, and zircaloy-4 that are supposed to be used as core materials in research reactors was required for irradiation at up to 8 reactor operation cycles at low temperature (<100°C). Therefore, three instrumented capsules were designed and fabricated for an evaluation of the neutron irradiation properties of the core materials (Graphite, Be, Zircaloy-4) of research reactors. The capsules were first designed and fabricated to irradiate materials at low temperature (<100℃) for a long cycle of 8 irradiation cycles at HANARO. Therefore, the safety of the new designed capsule should be fully checked before irradiation testing. Out-pile performance and endurance testing before HANARO irradiation testing was performed using a capsule under a 110% condition of a reactor coolant flow amount. The structural integrity of the capsule was analyzed in terms of a vibration-induced fatigue cracking of a rod tip of the capsule that is suspected to be the most vulnerable part of a capsule. Another two capsules were irradiated at HANARO for 4 cycles, and one capsule was transferred to a hot cell to examine the integrity of the rod tip of the capsule. After confirming the soundness of the 4 cycle-irradiated capsule, the remaining capsule was irradiated at up to 8 cycles at HANARO. Based on the structural integrity analysis of the capsule, an improved capsule design will be suggested for a longer irradiation test at HANARO.

1. Introduction

HANARO has been operated as a platform for basic nuclear research in Korea and the functions of its systems have been improved continuously since its first criticality in February 1995. It is now being successfully utilized in such areas as fuel and material irradiation tests and neutron transmutation doping to meet industrial, academic, and research demands. To support the national research and development programs on nuclear reactors and nuclear fuel cycle technology in Korea, rabbit and capsule irradiation facilities have been developed and actively utilized for the irradiation tests requested by numerous users [1]. Among the irradiation facilities, the capsule is the most useful device for coping with the various test requirements at HANARO. Most of irradiation testing using capsules have been performed under the condition of helium gas and at specimen temperatures of 300-500℃ within four reactor operation cycles at HANARO.

Recently, as a part of the research reactor development's project, irradiation testing of materials used as reflector materials in a research reactor, such as graphite, beryllium and zircaloy-4, was required for up to eight reactor operation cycles at low temperature (<100°C) of the specimens.

Therefore, a new capsule design was prepared for irradiating the reflector materials of research reactors [2]. Although the safety of a new capsule design should be fully checked before irradiation testing, irradiation testing of the capsules was undertaken under the condition of advanced out-pile endurance testing before the HANARO irradiation test from the 'Reactor Safety Review Committee of HANARO' to cope with the urgent project schedule. The out-pile endurance test was performed on a 110% condition of a reactor coolant flow amount. As the rod tip of the out-pile testing capsule failed during 7 operation cycles, the continuation of the irradiation testing at HANARO was discussed based on an analysis of the failure [3,4].

In this paper, the design and fabrication of the irradiation capsules for research reactor materials and the status of the irradiation testing at HANARO are described.

2. Design of Irradiation Capsule

2.1 Basic Design of Capsule

A typical HANARO material irradiation capsule consists of three main parts connected to each other: a protection tube, guide tube, and a capsule's main body, as shown in Figure 1. The main body including the specimens and instruments is a cylindrical shape stainless steel tube. The main body has 5 stages with independent micro-electric heaters, and contains thermocouples and neutron fluence monitors to measure the temperature and the fast neutron fluences of the specimens, respectively. Heaters and thermocouples are connected to a capsule temperature control system through a guide tube and connection box system. The remaining space in the closed capsule was filled with He gas and the temperature of the specimens was controlled in the range of 300-500℃ during reactor operation cycles at HANARO. The temperature of the specimens during an irradiation is initially increased by the gamma heating, roughly adjusted to an optimum condition by a gas control system, and then finally adjusted to a desired value by micro-electric heaters.

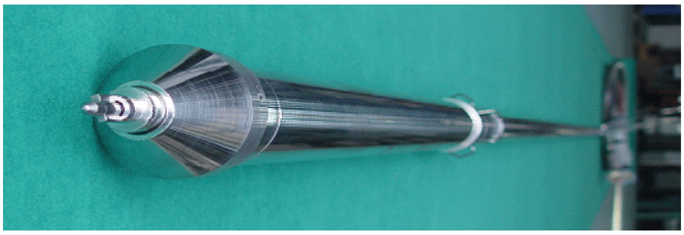

Fig. 1. Typical material irradiation capsule at HANARO

As the Irradiation of the reactor materials was required to be irradiated at low temperature of less than 100°C, the irradiation capsule was designed to be directly cooled by a reactor coolant of 30°C. The capsule was first designed at HANARO to have the coolant flow through the capsule to cool down the irradiation temperature of the specimens as shown in Figure 2 [3]. The capsule has the same outward shape of a typical capsule used for a closed He gas atmosphere.

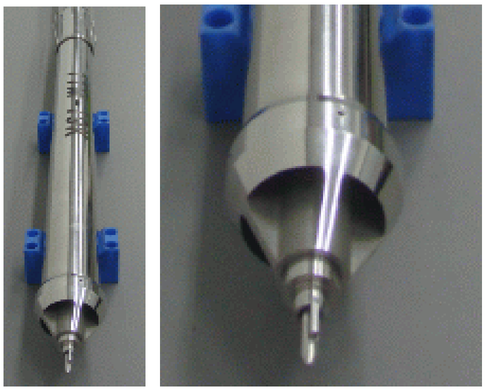

Fig. 2. The design of the capsule for irradiation of reactor materials

Based on a preliminary geometrical shape of specimens with different shapes as shown in Figure 3, a neutron flux and heat generation rates of capsule parts at 30MW thermal power of HANARO were evaluated using MCNP5 code. The specimens with different shapes are basically canned by a tube of 1 mm in thickness made of stainless steel. The surfaces of the canning tubes and the external tube come in contact with cooling water during the irradiation tests. The temperature of the specimens was evaluated using the ANSYS code, and the specimen size and allocation in the capsule were controlled to have a low temperature of less than 100℃ regardless of the shape of the specimen and the location in the axial direction of the reactor core.

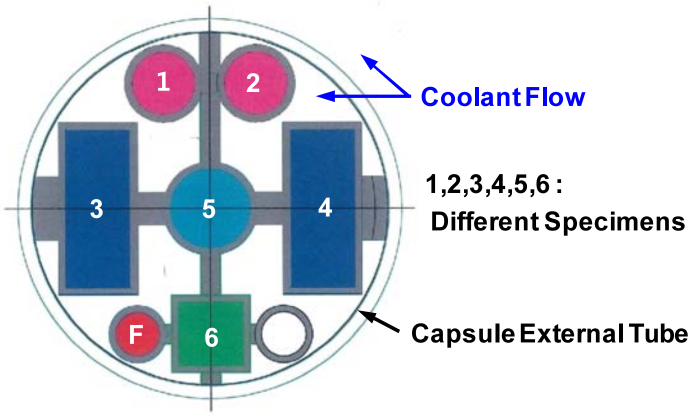

Fig. 3. Schematic cross section of the capsule main body

2.3 Out-pile Testing of Capsule

The safety of a new designed capsule should be fully checked before irradiation testing in the reactor. Based on the basic design of the capsule and nuclear and thermal analysis, an out-pile test capsule of 11M-19K was designed and fabricated [3]. To evaluate the soundness of the new capsule design, the capsule was out-pile tested in the single channel out-pile test loop. The capsule was tested and analyzed to satisfy several reactor requirements concerning the coolant flow and the vibration properties. Figure 4 shows the single channel test loop of the HANARO out-pile test facilities. The vibration characteristics of the capsule were measured by a laser vibrometer (Polytec Model VD-09).

Fig. 4. Measuring the vibration of a capsule installed in the single channel out-pile test loop

Owing to the internal flow of the coolant, the bottom part of the capsule was suspected to be susceptible to a vibration-induced fatigue failure. To strengthen the soundness of the bottom parts, the material of the rod tip was changed from stainless 304 to stainless 316L, and the welding method was also changed from TIG welding to an EB welding method.

An out-pile endurance test was performed on a 110% condition of a reactor coolant flow amount in the single channel out-pile test loop. As the rod tip of the out-pile testing capsule was failed during 7 operation cycles, as shown in Figure 5, continuation of the on-going irradiation testing of the capsules at HANARO was discussed based on an analysis of the failure [4].

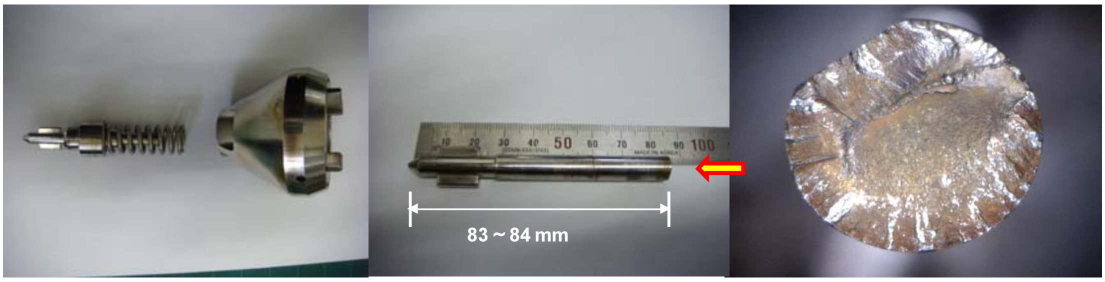

Fig. 5. Failed rod tip of the 11M-19K out-pile capsule

Figure 6 shows SEM micrographs of the fractured surface of the failed rod tip. It shows a typical appearance of torsion-induced fatigue fracture in the literature [5]. The fracture topography shows that cracks initiated at near the surface propagated into the central region and finally fractured, resulting in a brittle-ductile mixed fracture surface. Figure 7 shows that the out-pile test condition of 110% of a reactor coolant flow amount resulted in an increased directional coolant flow-induced vibration than a normal coolant flow condition of 100%. The amplitude of the vibration of the capsule was increased up to 128μm in the 110% coolant flow condition from 73μm of 100% coolant flow condition. The increased amplitude of vibration seems to be directly related to the failure of the out-pile test capsule. Based on the fractography and the increased amplitude of vibration of the capsule, the cause of the failure was attributed to a vibration-induced fatigue cracking. To clear the cause of the failure, the stress analysis and fatigue property of the failed part of the capsule are under examination.

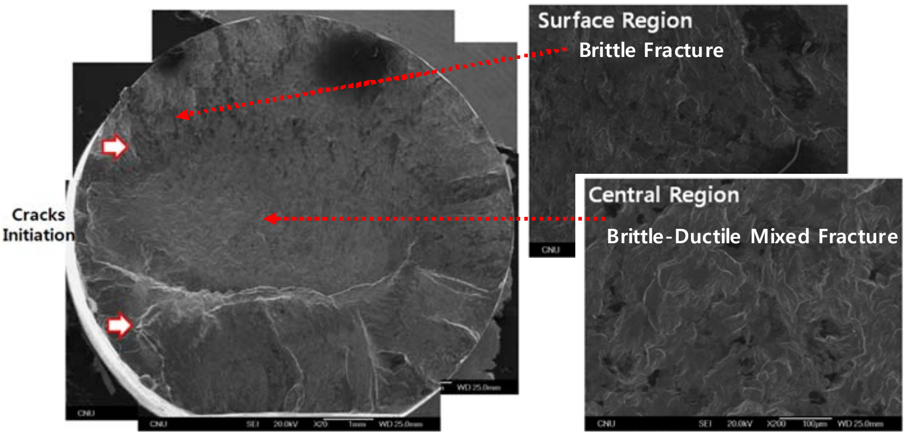

Fig. 6. SEM fractography of the failed rod tip of the 11M-19K capsule

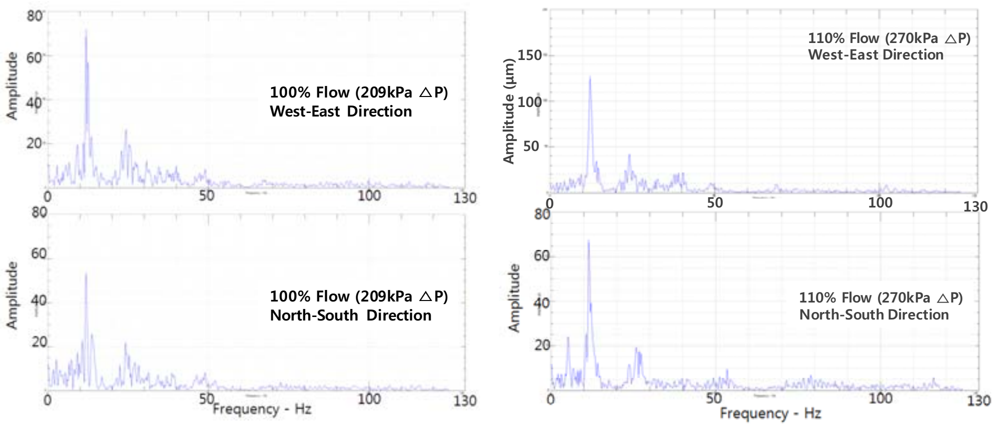

Fig. 7. Comparison of amplitude of vibration of 11M-19K capsule in 100% and 110% flow amount condition of reactor coolant

3. Irradiation Testing in HANARO

Based on the out-pile test results, two irradiation capsules of 11M-20K and 11M-21K were designed and fabricated [6]. Considering the increased amplitude of the vibration of the capsule during the out-pile endurance test of the 110% coolant flow condition, the capsule was estimated to be sound up to 7 irradiation cycles in HANARO of 100% coolant flow condition. Therefore, the irradiation capsules (11M-20K and 11M-21K) were loaded and irradiated in the CT and IR2 test holes of HANARO, respectively. Figure 8 shows a typical reactor core of HANARO with an irradiation capsule installed in the CT hole. The 11M-20K capsule was successfully irradiated for 4 cycles and transferred to a hot cell of IMEF. Figure 9 shows a variation of the temperatures of the specimens of the 11M-20K capsule irradiated in the CT Hole of HANARO (Cycle No. 83).

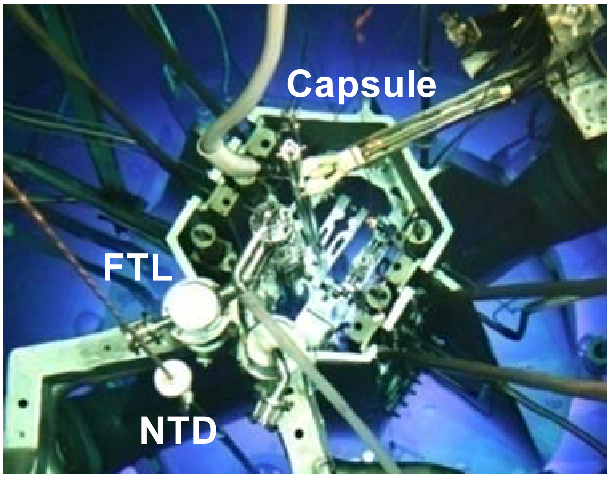

Fig. 8. Reactor core of HANARO with an capsule in the CT hole

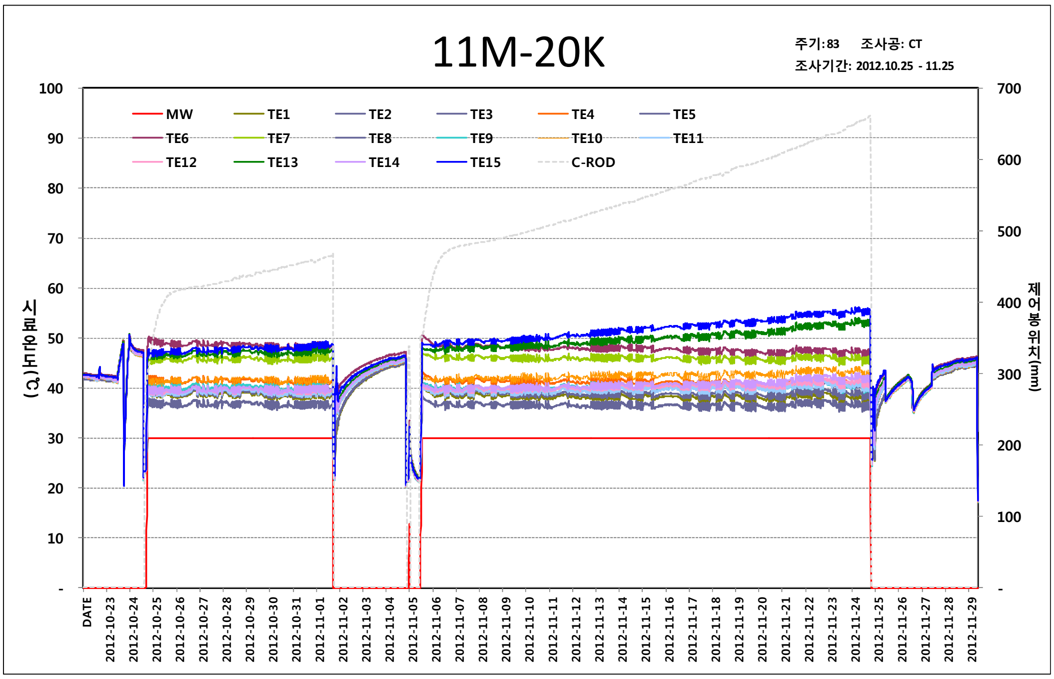

Fig. 9. Variation of the temperature of the 11M-20K capsule irradiated in the CT hole of HANARO (Cycle No. 83)

The rod tip of the irradiated capsule was sectioned into two parts, and the internal area was examined with an optical microscope and SEM to see an occurrence of fatigue cracks. Cracks or defects were not found in the rod tip of the irradiated capsule, as shown in Figure 10 and 11. Based on the soundness of the rod tip of the 11M-20K capsule, the irradiation of 11M-21K capsule that was already irradiated for 7 cycles in the reactor core will be extended to up to 8 cycles as required by the user.

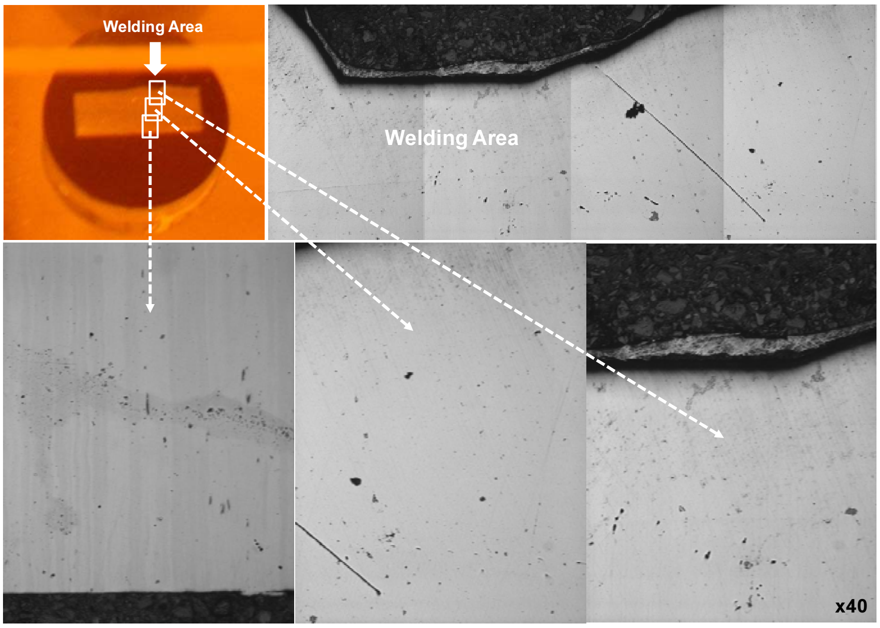

Fig. 10. Examination of the welding area of the rod tip of the 11M-20K irradiated capsule with optical microscope

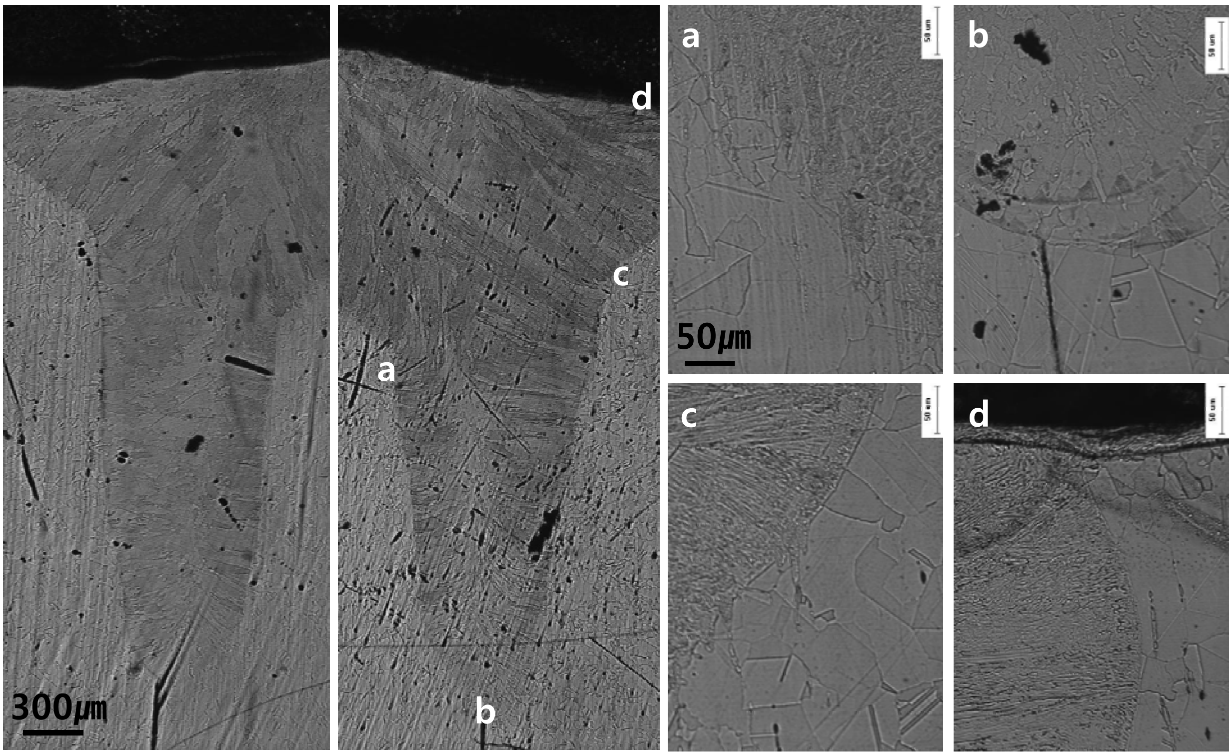

Fig. 11. Examination of the welding area of the rod tip of the 11M-20K irradiated capsule with SEM

4. Conclusions

A new capsule for irradiation at low temperature was designed, fabricated, and irradiated for an evaluation of the neutron irradiation properties of core materials (Graphite, Be, Zircaloy-4) of a research reactor for the National Project of 'Research Reactor Development'. Two capsules were first designed and fabricated to irradiate materials at low temperature (<100℃) for a long cycle of 8 irradiation cycles at HANARO. Therefore, the irradiation test of the capsules was approved under the condition of advanced out-pile endurance testing before the HANARO irradiation test from the 'Reactor Safety Review Committee of HANARO'. As the rod tip of the capsule was proven to be susceptible to a vibration-induced fatigue cracking, the safety of the irradiation capsules was thoroughly evaluated based on the out-pile and in-pile test results. The irradiation test of 11M-20K and 11M-21K capsules was successfully performed at HANARO for 4 and 8 cycles, respectively.

Acknowledgements

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