Current Status of R&D and PIE Program for ADS Material Development in JAEA

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Japan Atomic Energy Agency (JAEA) proposes transmutation of minor actinides (MA) by accelerator-driven systems (ADS). The ADS designed by JAEA is a system composed of a high intensity proton accelerator, a lead-bismuth eutectic (LBE) spallation target and a subcritical core. Since a beam window (BW) of ADS is exposed in a complex field of heavy irradiation by proton/neutron and corrosion by flowing LBE, JAEA plans to construct a materials irradiation facility at J-PARC. In the facility, a proton-beam extracted from J-PARC LINAC is injected to a LBE spallation target with 250 kW beam power, and post irradiation examination (PIE) is done for the samples such as BW of the target. Irradiation conditions in terms of temperature range, LBE flow rate, irradiation dose are from 400°C to 500°C, 1 m/s and 10 dpa/year, respectively. Along with conceptual design study of the facility, various R&Ds are being carried out by a LBE target mock-up loop “IMMORTAL” and a high temperature (550°C) material corrosion test loop “OLLOCHI”. Oxygen potential control systems for LBE flow have been also developed. As for PIE, specimen preparing procedure from the irradiated samples and BW including notchting method and LBE cleaning technology have been investigated. Testing techniques for small specimens under LBE have been also developed. In this paper, we described the current status of facility development with major focus on the PIE program.

KEYWORDS: ADS, LBE, spallation reaction, neutron production target, proton beam, PIE, J-PARC

1. Introduction

Japan Atomic Energy Agency (JAEA) has been developing accelerator-driven systems (ADS) for transmutation of minor actinide (MA)[1]. The ADS designed by JAEA is a system composed of a high-intensity proton accelerator, a lead-bismuth eutectic (LBE) neutron production target via the spallation reaction and a subcritical core cooled by LBE [2]. In the ADS, a beam window (BW) is exposed in both an intense proton beam and spallation/fission neutrons, and is corroded under flowing LBE. Thus, it is of critical importance to investigate integrity of materials used in such environment. Until now, some irradiation programs, such as STIP [3-5] and MEGAPIE [6-7], have produced many irradiation data in the spallation reaction environment. However, irradiation conditions of the data do not match to the ADS conditions in terms of (1) irradiation temperature up to 500 °C, (2) irradiation dose of about 20 dpa by both protons
and neutrons and (3) environment in flowing LBE. The irradiation temperature of the STIP specimens which ranges from 80 to 400 °C are lower than that of ADS and the most of the STIP specimens were irradiated without LBE. The MEGAPIE samples were irradiated in flowing LBE but irradiation temperature and dose are at most about 300 °C and 7 dpa, respectively, which are lower than those of ADS.

Thus, JAEA has proposed a program to construct a facility for material irradiation experiments at J-PARC to establish an irradiation database for candidate ADS structural materials and to investigate irradiation effects in flowing LBE environment from the engineering point of view. To realize the facility, various studies such as target design and component tests have been carried out and the results were summarized in a technical design report (TDR) [8].

After that, further design activities and R&Ds have been progressed in discussion of irradiation program, design of the LBE target, and a system for target exchange and maintenance of components. R&Ds for several important technologies required to build the facilities, such as a remote handling technique for target maintenance, the LBE components tests, the control of oxygen concentration in LBE, material corrosion tests in flowing LBE, are also underway. To perform the post irradiation examination (PIE), conceptual design of hot cells for the LBE target system maintenance and PIE of irradiated samples have been carried out. Techniques for PIE, such as remote handling for irradiated LBE treatment and sample preparation and, in particular, small specimen testing, have been developed.

In this paper, current status of results for R&Ds and a future program are presented.

2. R&D for Irradiation Facility

2.1 Target Design

A proton beam accelerated by the J-PARC LINAC to 400 MeV and 0.625 mA, thus the beam power is 250 kW, is injected to the facility. The proton beam is in a pulse mode with 25 Hz repetition rate and 500 μs pulse width. The proton beam profile is a Gaussian shape, and the width and peak current density of the proton beam are determined as 4 cm in FWHM and 30 μA/cm², respectively. The spallation target material is LBE. As shown in Fig. 1, the double tube type structure is adopted to the target vessel with considering cooling performance of the proton beam window and manufacturability. Inlet and outlet temperature of LBE are 400ºC and 500ºC, respectively. The maximum temperature of irradiation plates in the target is 550ºC. Expected lifetime of the target vessel is equal to either the maximum yearly operation time of 5,000 hours or the maximum yearly dose rate of 10 dpa. The target materials are SS316L and T91 for operating temperatures below and above 450ºC, respectively. The cover gas in the LBE circulation system is argon. A pressurized water type of heat exchanger for the secondary cooling system is selected to make it compact. For these conditions, the target system was designed as described in reference [8]. To increase the safety margin of the reference design of the target, the design has been further modified as shown in reference [9].
2.2 Irradiation Performance

Type irradiation samples are installed inside of the inner tube of the target as shown in Fig. 1. Size of the plates are 100 mm in length and 40 mm in width. Thickness is 2.0 mm or 3.3 mm. For the sample plates, dose and helium production rate were calculated [8]. Maximum irradiation dose is about 10 dpa/year at the front area of plate No.1 which is set at center of the sample holder. Dpa of the sample is 6-7 dpa/year, in average. Though the target container is to be exchanged by one cycle (5,000 hours), to accumulate irradiation dose, some of the irradiation plates are re-loaded to a new target for re-irradiation. Irradiation dose will reach to 20 dpa by 3 cycles irradiation. Maximum helium production rate is about 700 appm He/year at the front area of plate No. 1. Helium production in the sample is 300-400 appm He/year. After 3 cycles irradiation, it will reach to 900-1200 appm, which corresponds to operation condition of ADS.

2.3 R&Ds for LBE technology and remote handling technique

Along with conceptual design study of the facility and target, various R&Ds are being carried out. On the LBE technology development, LBE target mock-up loop “IMMORTAL (Integrated Multi-purpose Mockup for TEF-T Real-scale TArget Loop)” [10] and high temperature (550°C) material corrosion test loop “OLLOCHI (Oxygen-controlled LBE LOop for Corrosion tests in HIgh-temperature)” [11] have been manufactured and experiments have been started. Oxygen concentration control systems for LBE flow have been also developed. The PIE technology development will be described in section 3.2.

IMMORTAL is a demonstration loop for the target loop of the irradiation facility. Purposes of the loop are as follows; (1) dynamic behavior of heat removal, (2) confirmation and mastering of operation procedure, (3) integration test of individually developed components of LBE technologies, and (4) production of control sample for PIE of irradiation sample.

OLLOCHI is a corrosion test loop. Purposes of the loop are as follows; (1) corrosion data collection under ADS condition (max. temp. =550°C, ΔT= 100°C, oxygen concentration (CO) =10⁻⁵–10⁻⁶ wt.%, max. flow rate=2 m/s), (2) mechanical property tests in flowing LBE to investigate liquid metal embrittlement (LME), (3) investigation of
flow accelerated corrosion (FAC) in flowing LBE [12], (4) establishment of oxygen sensor and oxygen concentration control technology for large and high temperature LBE loop, and (5) development of purification system for LBE. Figure 2 shows flow-diagram of OLLOCHI. The loop has three test sections to perform both corrosion test and mechanical property test under flowing LBE.

As for remote handling technique, master slave manipulators (MSM), pipe cutter and automatic welding tools, and jigs for remote cutting and welding were tested. Tests using two MSMs on the mockup test device are underway. Further tests in high temperature and LBE residue are under preparation.

3. PIE Program

3.1 PIE Flow

The facility equips with three hot cells to facilitate the PIE sample preparation as shown in Fig. 3 [8]. The first one is the target maintenance cell for target exchange and target system maintenance. The second one is the sample preparing cell for specimen processing and assembling the re-irradiation target. The third one is the small cell for non-destructive inspections. Conceptual PIE flow was designed and reported [13]. In the hot cells, exchanging and dismantling the irradiated target, LBE cleaning, inspections of the target head and specimen preparation are conducted. Mechanical property tests, micro-structural observation and other investigations of the specimens are to be performed at other hot lab facilities in JAEA. Details of the processes are described in the following sections.
3.2 R&Ds for the PIE Program

In the irradiation facility, unlike capsule irradiation in reactors or accelerators, specimens are prepared from the BW and the irradiation plate samples by remote handling. It is necessary to develop new technologies, for instance, LBE cleaning technology and specimen preparing methods from the BW and irradiation plates. Testing techniques for small specimens and in LBE are also necessary to be developed.

1) LBE cleaning and off-gas processing for sample preparation

As the samples are irradiated in LBE, it is anticipated that alpha particle emitters of $^{210}\text{Po}$ and $^{208}\text{Po}$, which are reaction products of LBE, could be adhered on the surface of samples. To perform the PIE effectively, it is necessary to remove Po. As a LBE cleaning method, brushing in Silicon oil or glycerin at 170-180°C, mixed solution (acetic acid, hydrogen peroxide and ethanol) and nitric acid [14] are well known. To select LBE cleaning method for the irradiation facility, cleaning performance, applicability to remote handling and treatment of wastes are to be considered. Off-gas treatment is essential for safety operation and licensing. Collection technique for off-gases needs to be developed for additional treatment.

2) Remote handling system for sample preparation

As the irradiated target and sample plates are highly activated, all specimens have to be processed by remote handling. Electro discharge machining (EDM) is the most experienced and promising method. MEGAPIE samples were cut out by wire type EDM. Die-sinking type EDM is used for sample cutting from SNS and J-PARC targets. Until now, both types are candidates. Though most of specimens are plate type specimen with rectangle section, circular section specimens are preferable to perform axial fatigue test. Mock-up test to prepare the specimen with circular section has been finished by special lathe machining as shown in Fig. 4. For notching technique to perform miniature Charpy and fracture toughness tests, disk wheel type and EDM type were considered and then, the disk wheel method was selected as the first candidate. Cutting and polishing techniques for metallurgical and cross-sectional observation have been established through the PIE of STIP and MEGAPIE specimens. Thinning techniques for TEM / small punch (SP) specimens have also been established. They were thinned by mechanical polishing with brass jigs. TEM discs were thinned by FIB or electro-chemically polishing for TEM observation.

3) Testing techniques under LBE

Small specimen testing technique (SSTT) is one of key technologies for nuclear material development. Especially, for accelerator irradiation facilities, irradiation
volumes are very small and the irradiated specimens are highly activated. To use the irradiation volume effectively and to decrease the radiation dose, SSTT is an indispensable procedure. Not only testing techniques, but also specimen size effect is important. Following SSTT will be adopted for the PIE of the facility. (1) tensile / slow strain rate tensile (SSRT) test with SS-J3 specimen, (2) fatigue test with Φ1.6 mm × 5.0 mm gauge specimen, (3) miniature Charpy test with 3.3 mm × 3.3 mm specimen, (4) SP test with Φ1.0 mm steel ball, (5) bending test with 2.0 mm × 2.0 mm specimen, etc. Some of the above mentioned testing will be performed in LBE to investigate liquid metal embrittlement (LME). LBE vessel has been installed to testing machine and some tests have started.

4. Summary

Concerning the irradiation program of the J-PARC’s irradiation facility, design activities of the LBE target have been progressed. R&Ds for several important technologies required to build the irradiation facility, the mockup loop tests using IMMORTAL, material corrosion tests using OLLOCHI and remote handling tests have been progressed. Design of hot-cells for PIE and PIE operation flow have been studied. R&Ds for PIE, LBE cleaning technique, specimen preparation methods from the BW and irradiation plates, testing techniques using small specimens and testing techniques in LBE have been examined. A mock-up test for specimen preparation is planned.

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