Key achievements in elementary R&Ds on water-cooled solid breeder blanket for ITER Test Blanket Module in JAERI

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Abstract. This paper presents significant progress in research and development (R&D) of key elementary technologies on the water-cooled solid breeder blanket for the ITER test blanket modules (TBMs) in JAERI. Development of module fabrication technology, bonding technology of armors, measurement of thermo-mechanical properties of pebble beds, neutronics studies on a blanket module mockup, and tritium release behavior from Li_2TiO_3 pebble bed under neutron pulsed operation condition are summarized.

By the improvement of heat treatment process for blanket module fabrication, a fine-grained microstructure of F82H, can be obtained by homogenizing it at 1150 ^{o}C followed by normalizing at 930 ^{o}C after the Hot Isostatic Pressing (HIP) process. Moreover, a promising bonding process for a tungsten armor and an F82H structural material was developed by using a solid state bonding method based on uniaxial hot compression without any artificial compliant layer. As a result of high heat flux tests of F82H first wall mockups, it was found that the thermal fatigue lifetime of F82H can be predicted by using Manson-Coffin's law. As for R&Ds on a breeder material, Li_2TiO_3, effective thermal conductivity of Li_2TiO_3 pebble was measured under compressive force simulating the ITER TBM environment. The increase in the effective thermal conductivity of the pebble bed was about 2.5 % at the compressive strain of 0.9 % at 400 ^{o}C. Neutronic performance of the blanket module mockup has been carried out by the 14 MeV neutron irradiation. It was confirmed that the measured tritium production rate agreed with the calculated values within about 10 % difference. Also, tritium release from a Li_2TiO_3 pebble bed was measured under pulsed neutron irradiation conditions simulating the ITER operation.

1. Introduction

Development of key elementary issues on the water-cooled solid breeder blanket for the ITER test blanket modules (TBMs) has widely progressed in JAERI, and it can be shifted into a new stage, where integrated performance of TBM structures will be demonstrated by scalable mockups. The present paper presents the key achievements of the latest R&D activities on the ITER TBM development in JAERI. Demonstration of blanket functions under fusion environments, e.g., by installing TBMs in ITER, is considered as one of the most important milestones. In the previous paper [1], conceptual design activities and supporting R&Ds on the solid breeder blanket were presented. The present paper describes the significant R&D progress for ITER TBMs, which includes development of module fabrication technology, bonding technology of armors, measurement of thermo-mechanical properties of pebble beds, neutronics studies on a blanket module mockup, and tritium release behavior from a Li_2TiO_3 pebble bed under pulsed neutron irradiation conditions.

2. Improvement of Heat Treatment Process for Blanket Module Fabrication

In the TBM design, a reduced activation ferritic steel, F82H, is utilized as a structural material. The casing of a blanket module including the first wall is manufactured by using a

Hot Isostatic Pressing (HIP) process performed above 1000 ^{o}C. The basic feasibility of the HIP process was shown previously. However, it was necessary to improve the heat treatment process of the HIP bonded material since the fracture toughness of F82H degraded due to grain size coarsening by the thermal transient by the high temperature HIP process. Therefore, a heat treatment test was carried out to find a suitable heat treatment process which could recover the original grain size of F82H after the HIP process [2]. Figure 1 shows the typical microstructure of F82H obtained in the heat treatment test. According to the test, it was found that the conventional normalizing temperature of 1040 ^{o}C for F82H was insufficient to normalize the prior grain size of F82H, and was essential to homogenize F82H above 1100 ^{o}C prior to the normalizing. In addition, F82H with coarse grains can be recovered by the homogenizing followed by low temperature normalizing below 1000^{o}C. Based on this result, homogenizing at 1150 ^{o}C followed by normalizing at 930 ^{o}C is proposed as a suitable heat treatment condition for F82H. The advantage of this technique is that the thermal transient of the HIP process conducted over 1150 ^{o}C can be utilized as the homogenizing process of F82H, which can simplify the post-HIP heat treatment of the TBM fabrication. Moreover, this technique is effective for realizing the better mechanical performance of TBMs made of F82H after the HIP process.

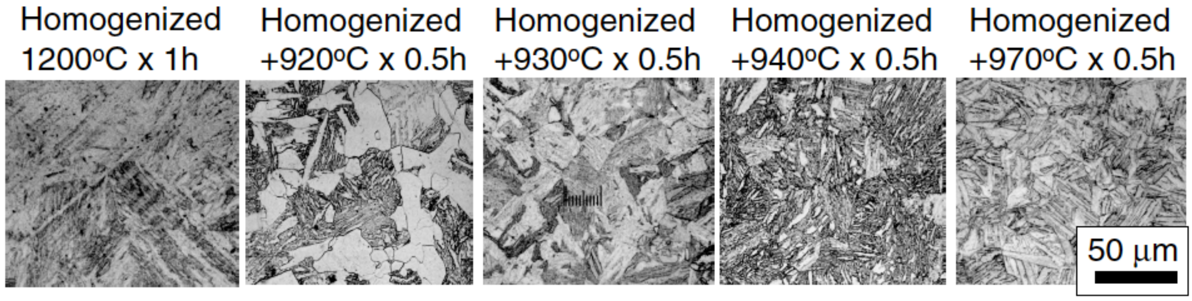

FIG. 1. Microstructure of F82H after homogenizing following normalizing at various temperature.

3. Investigation of Tungsten Armor Bonding Process for Blanket Module Fabrication

Tungsten is considered as one of the candidate armor materials for the first wall of the TBMs. Hence, it is necessary for the fabrication of TBMs to establish the bonding technology for tungsten and F82H joint. So far, braze technique has been developed as an extension of the bonding technique for the plasma facing components of ITER. However, major concern of the braze joint is a degradation of the braze material due to neutron irradiation. Therefore, a direct bonding method is preferable for the first wall of TBMs. On the other hand, large difference of the thermal expansion coefficient between tungsten and F82H will be more serious problem for the direct bonding method. A basic bonding test was carried out by using a solid state direct bonding method based on uniaxial hot compression [2]. In this method, tungsten armor is directly bonded onto F82H substrate without any artificial interlayer under compression loading at elevated temperature. Schematic of this bonding method is shown in FIG. 2. The bonding temperature was 960 ^{o}C for 30 min under a compression loading of 20 MPa. Figure 3 shows a result of the scanning-electron microscope observation of tungsten armor bonded onto F82H plate. No significant defects can be found along the bond interface. A thin interlayer was formed at the bond interface as shown in FIG. 3. According to an elemental analysis of the bond interface, this thin interlayer was found to be a ferritic phase. This ferritic phase was mainly induced by the decarburization from the martensitic phase of F82H. It is considered that this compliant layer of the ferritic phase can lead to successful bonding for the tungsten and F82H joint even without an artificial interlayer. This result gives promising prospect for the direct bonding of tungsten armor onto the first wall of TBMs. Further R&Ds on the durability and reliability of this joint are essential to utilize this method for the TBM fabrication.

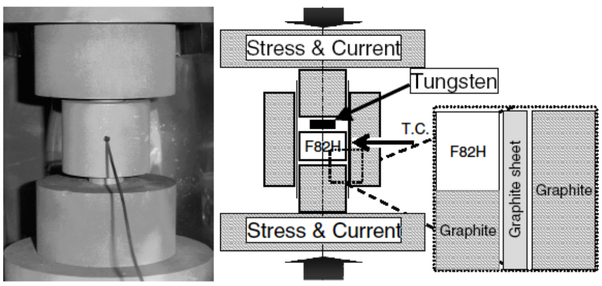

FIG. 2. Schematic of uniaxial hot compression method for the tungsten and F82H joint.

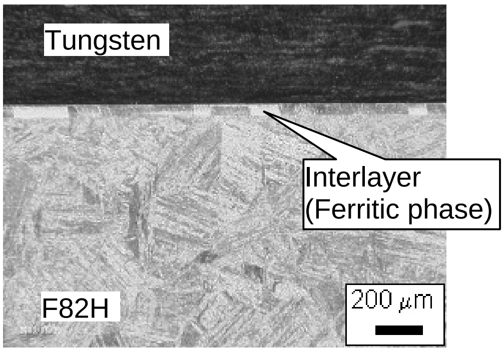

FIG. 3. Bonding interface of tungsten and F82H by using uniaxial hot compression.

4. Thermal fatigue lifetime of F82H first wall mockup

Another important issue of F82H as a structural material of TBMs is to establish the adequate lifetime evaluation method for thermal fatigue behavior because the TBM is subjected to a cyclic thermal loading during the repetitions of ITER operation. To investigate the durability of F82H first wall against a cyclic thermal stress simulating the ITER operation, thermal fatigue experiments of F82H mockups were carried out. Figure 4 shows a schematic of the F82H mockup. The mockup with a screw cooling tube was fabricated from a single F82H plate by milling process. It has no welded/bonded piece except for coolant connectors to avoid an initial bond/weld defect and to obtain precise thermal fatigue data. In the thermal fatigue experiment, the mockup was cyclically heated from the upper side by an electron beam irradiation. Figure 5 shows a fatigue lifetime of F82H obtained from the experiments at heat fluxes of 3 and 5 MW/m^2. At a heat flux of 5MW/m^2, a water leakage occurred from the cooling tube at about 650 cycles due to thermal fatigue. The fatigue crack initiated from the outer surface of the cooling tube as shown in FIG. 4. In addition, the fatigue lifetime estimation based on a 3D finite element elastoplastic stress was carried out. It was found that the thermal fatigue lifetime of F82H could be predicted by using Manson-Coffin's law.

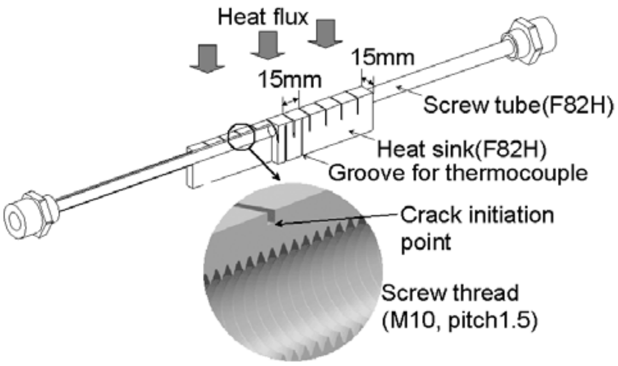

FIG. 4. Schematic of F82H first wall mockup.

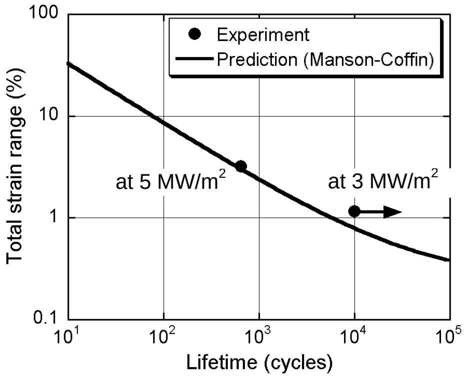

FIG. 5. Thermal fatigue lifetime of F82H.

5. Effective thermal conductivity of a breeder pebble bed at elevated temperature

It is promptly needed for the structural design of the TBMs to obtain thermo-mechanical behavior of the breeder pebble at elevated temperature equivalent to the operational condition of the TBMs. A new test apparatus has been developed to measure the effective thermal conductivity of pebble beds. The pebble bed specimen with an Al_2O_3 container is installed into a tensile test facility. The effective thermal conductivity of the pebble bed can be measured by using a hot wire method under more realistic loading conditions which simulates the consolidation of the pebble bed due to thermal expansion. By the preliminary experiment using Li_2TiO_3 pebble bed, the increase of the effective thermal conductivity of the pebble bed was observed to be about 2.5 % under the compressive strain of 0.9 % at 400 °C. This trend was also observed at higher testing temperature up to 700 ^{o}C as shown in FIG. 7. This apparatus is expected to clarify the effective thermal conductivity of pebble beds under creep conditions or cyclic stress simulating the TBM conditions.

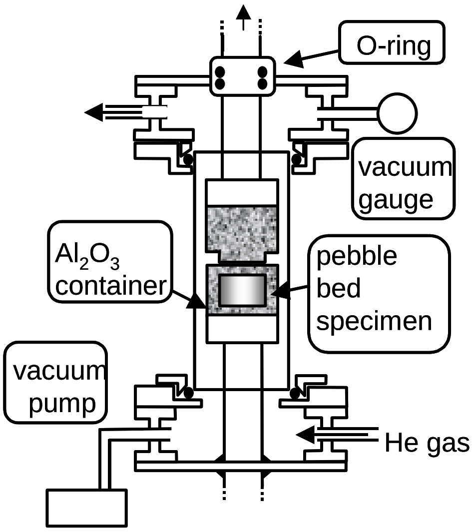

FIG. 6. Test apparatus for the measurement of the effective thermal conductivity of pebble beds.

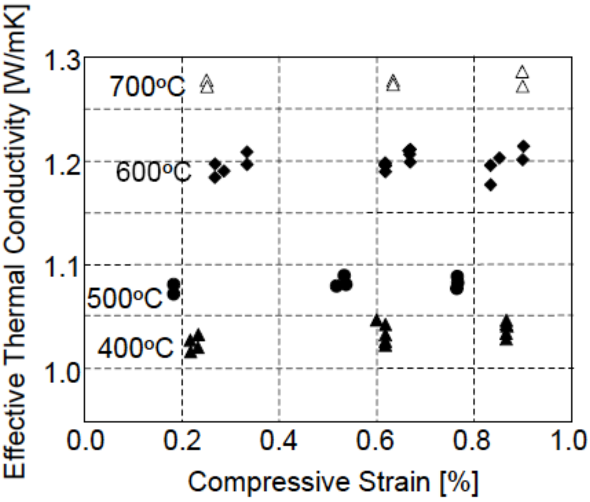

FIG. 7 Effective thermal conductivity of a compressed Li_2TiO_3 pebble bed

6. Neutronics Study of the blanket module mockup

One of the main roles of the ITER TBM is to demonstrate the tritium breeding function under fusion environment. Though the tritium breeding ratio over 1.0 is not necessary for TBMs to achieve, the accuracy of calculated tritium production rate (TPR) of the TBMs should strictly be evaluated to establish the numerical method on the neutronic performance of a blanket system for the design of future fusion reactors. Hence, neutronic performance of the blanket module mockup consisting of three layers of Li_2TiO_3 as a tritium breeder, beryllium as a neutron multiplier and F82H as a structural material, has been carried out by the 14 MeV neutron irradiation. Based on the experiment and the calculation on this simplified system shown in FIG. 8, the difference on the TPR between analytic values and the experimental values (C/E) was estimated. It was confirmed that the measured TPR in the experiment agreed with the calculated values within about 10 % as shown in FIG. 9.

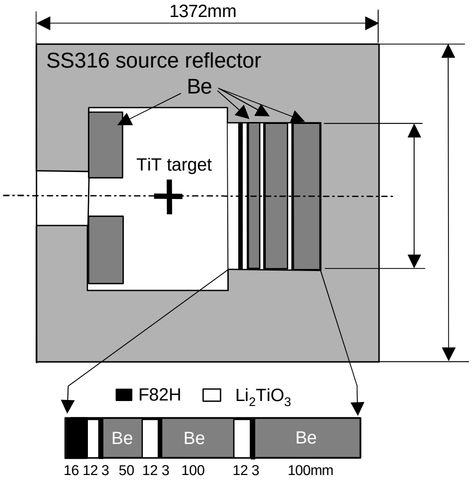

FIG. 8. Schematic of the experimental assembly consisting of three layers of the breeding blanket mockup.

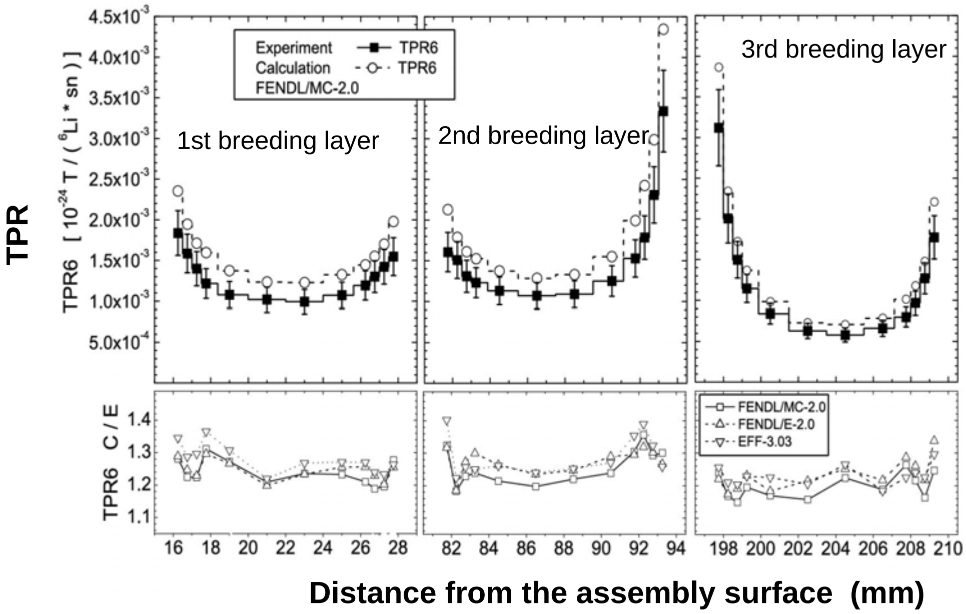

FIG. 9. TPR for Li_2TiO_3 pellets obtained by the experiment and calculations and the ratio of the calculated results to the experimental results.

7. Tritium release behavior from Li_2TiO_3 pebble bed under neutron pulse operation

JAERI is developing tritium breeding materials in the shape of small pebbles. It is essential in this work to perform in-pile functional tests of a mockup assembly containing the produced pebbles. In order to realize the in-pile functional tests, various irradiation devices have been developed, such as 1) a pulse irradiation device described below, 2) multi-paired thermocouples for measuring temperatures at many points, and 3) a highly sensitive and responsive self-powered neutron detector (SPND). An integrated in-pile test is being performed in the Japan Materials Testing Reactor (JMTR) by using these devices [3, 4].

In testing of the TBM, the 400 second cyclic-pulsed operation has been planned as the normal condition. Therefore, in-situ tritium release performance is needed to be demonstrated under simulated conditions of the cyclic-pulsed operation of ITER. A schematic view of a simulated ITER pulse-operation mockup is given in FIG. 10 [5]. This mockup is equipped with a window made by hafnium (Hf), which absorbs thermal neutrons. The Hf window is rotated by a stepping motor installed in this mockup, which enables intermittent neutron irradiation in simulated pulse operation. The mockup contains a binary pebble bed of Li_2TiO_3; namely smaller (about 0.3 mm in diameter) and larger (about 2 mm) pebbles were mixed to be installed in the in-pile mockup. The packing fraction of the pebbles in this bed is 81.3%. It was shown earlier in a steady state operation that almost all the tritium generated in the Li_2TiO_3 pebble was released at temperatures above 300 ^oC, which is the lowest design temperature of the breeder bed. In the pulse operation, the temperature at the outside edge of the pebble bed increased from 350 to 400 ^oC immediately after the window of Hf neutron absorber was turned toward the reactor core. In contrast, the tritium release rate increased gradually. The ratio of tritium release rate to tritium generation rate at the high power, $(R/G)_{high}$, approached the saturated value of unity with a time constant of about 3 h in a brief approximation of linear response, as shown in FIG. 11. Overall tritium release behavior under the pulsed operation was almost the same as that under the continuous irradiation condition. The time constant for tritium release was much longer than the time constants for changes in the thermal neutron flux and the irradiation temperature of the pebble bed. Thus, the effect of the pulsed operation on the tritium release behavior was clarified, and good tritium release performance was demonstrated.

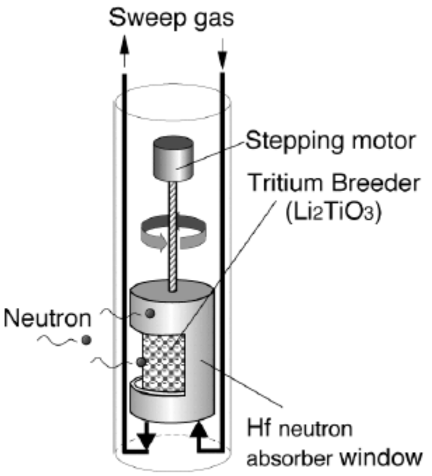

FIG. 10. Schematic of pulse operation mockup.

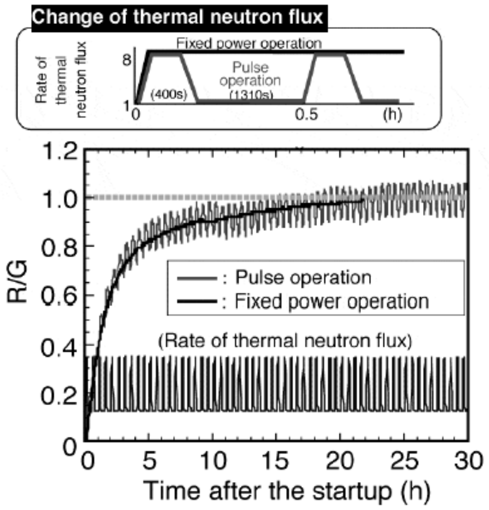

FIG.11. Tritium release behaviors under conditions of pulsed and fixed power operation.

Conclusions

Key achievements in elementary R&Ds on the development of water-cooled solid breeder blanket for ITER Test Blanket Module in JAERI are summarized below. Based on these promising results, the integrated performance of the TBMs will be demonstrated in JAERI by using scalable mockups.

1) A suitable post-HIP heat treatment for the fabrication of TBMs made of F82H was proposed. The heat treatment process of homogenizing at 1150 ^oC followed by normalizing at 930 ^oC can recover from the coarse grains of F82H caused by a HIP process.
2) A direct bonding method of tungsten armor onto F82H first wall has been developed by using a solid state bonding method based on uniaxial hot compression.
3) Thermal fatigue behavior of the F82H first wall mockup was investigated. It was found that the thermal fatigue lifetime of the F82H mockup could be predicted by Manson-Coffin's law based on a 3D elastoplastic stress analysis.

4) A new test apparatus has been developed to measure the effective thermal conductivity of the pebble beds. The effective thermal conductivity of the Li_2TiO_3 pebble beds was measured in this facility. The increase of the effective thermal conductivity was observed to be about 2.5 % under the compressive strain of 0.9 % at 400 ^oC.
5) Neutronic performance of the blanket module mockup consisting of three layers, Li_2TiO_3, beryllium and F82H, has been carried out by the 14 MeV neutron irradiation. The difference on the TPR between analytic values and the experimental values was estimated. It was confirmed that the measured TPR in the experiment agreed with the calculated values within about 10 %, which shows the validity of the analysis method.
6) In-situ tritium release behavior from the simulated ITER pulse-operation mockup was studied by using JMTR. This work revealed that overall tritium release behavior under the pulsed operation was almost same as that under the continuous operation, and also demonstrated the good tritium release performance of the Li_2TiO_3 pebble bed.

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