Development of Advanced Blanket Materials for Solid Breeder Blanket of Fusion Reactor

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Abstract. The design of advanced solid breeding blanket in the DEMO reactor requires the tritium breeder and neutron multiplier that can withstand the high temperature and high neutron fluence, and the development of such as advanced blanket materials has been carried out by the cooperation activities among JAERI, universities and industries in Japan. The Li_2TiO_3 pebble fabricated by wet process is a reference material as a tritium breeder, but the stability on high temperature has to be improved for application to DEMO blanket. As one of such the improved materials, TiO_2-doped Li_2TiO_3 pebbles were successfully fabricated and TiO_2-doped Li_2TiO_3 has been studied. For the advanced neutron multiplier, the beryllides that have high melting point and good chemical stability have been studied. Some characterization of $Be_{12}Ti$ was conducted, and it became clear that $Be_{12}Ti$ had lower swelling and tritium inventory than that of beryllium metal. The pebble fabrication study for $Be_{12}Ti$ was also performed and $Be_{12}Ti$ pebbles were successfully fabricated. From these activities, the bright prospect was obtained to realize the DEMO blanket by the application of TiO_2-doped Li_2TiO_3 and beryllides.

1. Introduction

The design of advanced fusion blanket has been studied to realize DEMO reactors in Japan. In the design under development, coolant temperature is more than 500˚C, and it is required for the tritium breeder and neutron multiplier in the blanket to accommodate the high temperature and high neutron fluence. Therefore, the development of advanced blanket materials has been pursued to realize higher performances required. In this paper, the collaborative activities among JAERI, universities and industries in Japan are reported on the development of these advanced materials.

For the tritium breeder, lithium titanate (Li_2TiO_3) pebbles with a diameter of 0.3-2mm were chosen as a tentative reference material from viewpoints of tritium recovery, chemical stability and so on. Concerning a pebble fabrication method, a wet process was chosen from points of mass productivity, ^{6}Li recycle, etc., and was tested. From the results, it became obvious that a specification target (density: 80-85%T.D., grain size: <5μm) of tritium breeder was reached by wet process. In order to estimate the tritium release behavior at the lower temperature which has large effects on fusion blanket design, in-situ tritium recovery experiments with Li_2TiO_3 pebbles fabricated by wet process were carried out at the Japan Materials Testing Reactor (JMTR) [1] and it became obvious that Li_2TiO_3 was a good material. However, it was clear that the stability at high temperature was bad. Therefore, the development of TiO_2-doped Li_2TiO_3 is started as improved tritium breeder. In this study, the characteristics of this material are compared to that of Li_2TiO_3 and the application on the condition of DEMO blanket is also estimated.

For the neutron multiplier, beryllium metal (Be) is a reference material in the blanket design. However, it may not be applicable to the DEMO blanket that requires high temperature (~900˚C) and neutron dose (~20,000appmHe, ~50dpa), because of high reactivity and large swelling. Therefore, it is necessary to develop the advanced material for a neutron multiplier that has high temperature resistance and high radiation resistance. Beryllides such as $Be_{12}Ti$ and $Be_{12}V$ have been expected as promising candidates for advanced neutron multipliers from the viewpoints of high melting point, high beryllium content, low radio activation, good chemical stability, etc. Several characterizations have been studied for $Be_{12}Ti$ to evaluate the advantage. And the pebble fabrication study of $Be_{12}Ti$ and $Be_{12}V$ was curried out.

2. Development of improved tritium breeder

2.1 Characterization of TiO_2-doped Li_2TiO_3

The TiO_2-doped Li_2TiO_3 in which TiO_2 contents are different, was examined in order to make clear TiO_2 doping effect. As the one of un-irradiated material properties, the effect of TiO_2 content on thermal properties of Li_2TiO_3 was measured and optimum TiO_2 content in Li_2TiO_3 was evaluated in this study. First, specific heat and thermal diffusivity of TiO_2-doped Li_2TiO_3 were measured by differential scanning calorimeter method and laser flush method, respectively.

The results of specific heat measurement showed that specific heat of TiO_2-doped Li_2TiO_3 (TiO_2 content:2.5-20mol%) coincided with that of un-doped Li_2TiO_3 within the range of 10%. Thermal diffusivity of TiO_2-doped Li_2TiO_3 is shown in FIG. 1. The difference of thermal diffusivity between TiO_2-doped Li_2TiO_3 and un-doped Li_2TiO_3 was up to 15%. From these results, it was estimated that the effective thermal conductivity of pebble bed using TiO_2-doped Li_2TiO_3 pebbles was almost the same as that using un-doped Li_2TiO_3 pebbles. And, the results of specific heat measurement showed that the performance in phase transformation of TiO_2-doped Li_2TiO_3 (TiO_2 content: 14mol%) on around 960˚C at which the phase of Li_2TiO_3 changed to unstable state phase ($\beta+\gamma$ phases) was almost the same as that of Li_2TiO_3. Additionally, the preliminary test for the estimation of irradiation damage of TiO_2-doped Li_2TiO_3 was performed by means of the triple ion beams (0.25MeV H^+, 0.6MeV He^+ and 2.4MeV O^{2+}) [2] and it was also confirmed that the estimation on transformation mechanism of TiO_2-doped Li_2TiO_3 was possible. From these results, it was considered that the optimum TiO_2 content in Li_2TiO_3 was less than 14mol%.

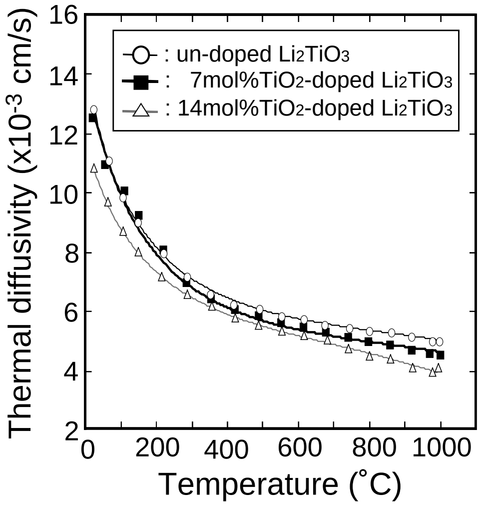


FIG. 1. Thermal diffusivity of TiO_2-doped Li_2TiO_3.

2.2 Fabrication technology of TiO_2-doped Li_2TiO_3 pebbles

The fabrication tests of un-doped and TiO_2-doped Li_2TiO_3 pebbles (TiO_2 content : 2.5, 5 and 10mol%) were examined by two kinds of wet processes [3] (wet process with dehydration reaction and wet process with substitution reaction) and characteristics of pebbles were evaluated. Sintered temperature decreased about 100˚C when TiO_2 content in the TiO_2-doped Li_2TiO_3 pebbles was 5mol%. Relationship between grain size and sintered density of un-doped and TiO_2-doped Li_2TiO_3 pebbles fabricated by the wet process is shown in FIG. 2. Especially, it was obvious that the grain size of the pebbles with 85%T.D. was less than 5μm on 5mol% TiO_2 doped in Li_2TiO_3 pebbles. No grain growth occurred in 5mol% TiO_2-doped Li_2TiO_3 at the annealing temperature of 900˚C and 1000˚C for 20 min. by the annealing test. The collapse strength of 5mol% TiO_2-doped Li_2TiO_3 pebbles was 1.5 times as large as that of un-doped Li_2TiO_3 pebbles. From these results, bright prospect was obtained concerning the fabrication of the TiO_2-doped Li_2TiO_3 pebbles of diameter 0.2-2mm by the wet process.

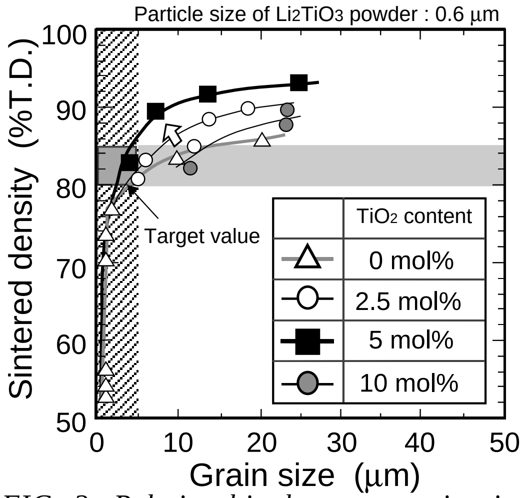


FIG. 2. Relationship between grain size and sintered density of Li_2TiO_3 and TiO_2-doped Li_2TiO_3 pebbles.

3. Development of advanced neutron multiplier

3.1 Characterization of $Be_{12}Ti$

3.1.1 Compatibility

The compatibility test of $Be_{12}Ti$ was carried out with structural material (SS316LN) and tritium breeder (Li_2TiO_3) at 600˚C, 700˚C and 800˚C up to 1000h by annealing [4,5]. The results of the compatibility for SS316LN are shown in FIG. 3. It was obvious that the compatibility between $Be_{12}Ti$ and SS316LN was much better than that of between Be and SS316LN. The thickness of reaction layer between $Be_{12}Ti$ and SS316LN at 800˚C was one tenth of that for Be.

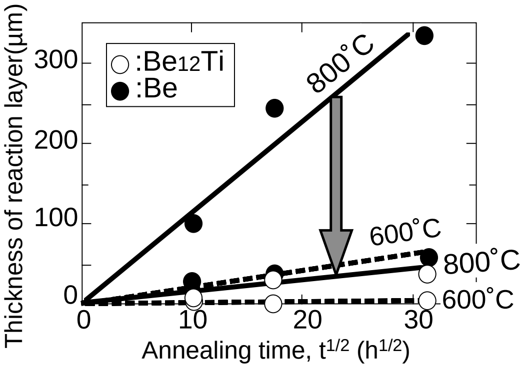


FIG. 3. Results of compatibility test

As to the compatibility between $Be_{12}Ti$ and Li_2TiO_3, the reaction products on the $Be_{12}Ti$ and Be in contact with Li_2TiO_3 were not found at any temperatures up to 1000h. On the other hand, the diffused Li into Be was identified at 800˚C for 300h and 1000h. The results of these compatibility evaluations showed that $Be_{12}Ti$ had the advantages for high temperature.

3.1.2 Swelling property

$Be_{12}Ti$ and Be specimen were irradiated up to ~$4x10^{24}n/m^2$ (E>1MeV) at 500˚C in JMTR [6]. Helium production rate and dpa for Be were about 70appmHe and 0.5dpa, respectively. Swelling was calculated from the dimension and weight measurement results for the neutron irradiated $Be_{12}Ti$ disk heated at 1100°C for 1h after irradiation. The swelling value of $Be_{12}Ti$ was less than 3%. On the other hand, the swelling value of Be was ~60%. From these results, swelling of $Be_{12}Ti$ under the high temperature neutron irradiation can be expected smaller than that of Be.

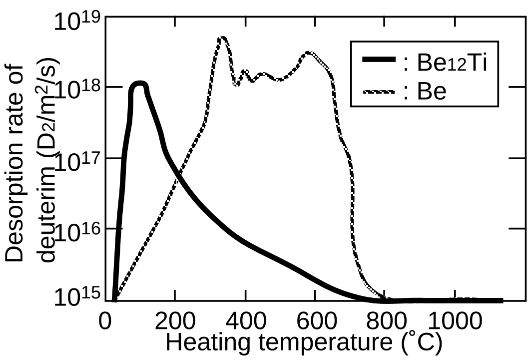


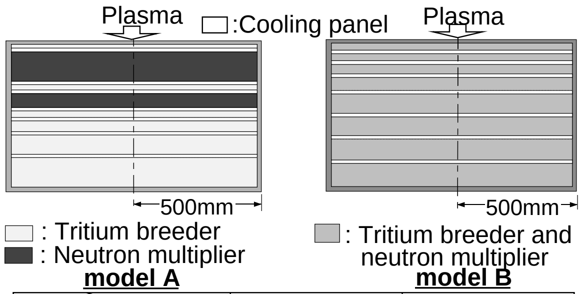
FIG. 4. Desorption rate of deuterium

3.1.3 Tritium inventory

The desorption property of deuterium was evaluated by the heating test after deuterium implantation [7]. A part of results is shown in FIG. 4. Deuterium was implanted up to $1x10^{21}$ ions/m^2 at room temperature. The profile of desorption rate for $Be_{12}Ti$ has a peak at about 100˚C. On the other hand, the peak temperature of desorption rate for Be is higher (350˚C-700˚C) than that for $Be_{12}Ti$. The amount of 20% in implanted deuterium is retained in Be around 700˚C. These results made clear that the deuterium desorption property of $Be_{12}Ti$ was more superior than that of Be. It is obvious that the tritium inventory from $Be_{12}Ti$ is much smaller than that for Be.

3.1.4 Evaluation of TBR

The evaluation of Tritium Breeding Ratio (TBR) using beryllide as a neutron multiplier was carried out using two models that were mono material packing and mixed material packing (tritium breeder and neutron multiplier) [8]. The tritium breeder was Li_2TiO_3 of 85%T.D. and 50at% ^6Li enrichment. The packing fraction of pebble beds was 80%P.F. DOT3.5 code and FUSION-40 (based on JENDL3.2) were used for the calculation. The neutron wall load was 5MW/m^2. Assumed temperature in the blanket was as same as current blanket design. The result of the TBR evaluation is shown in FIG. 5. TBR of blanket with $Be_{12}Ti$ pebbles was only 10% smaller than that with Be pebbles. It is considered that this value is within design window and the improvement by raising temperature is expected. It is also made clear that mixed pebble bed of tritium breeder and neutron multiplier would improve TBR 10% better.



neutron multiplier \ Model	model A	model B
Be	1.27	1.32
$Be_{12}Ti$	1.12	1.23

FIG. 5. The results of TBR evaluation

Ion	Fluence (n/m^2)	
Electron	$1.19x10^{23}$	$2.86x10^{25}$
Helium	$1.61x10^{14}$	$3.87x10^{16}$

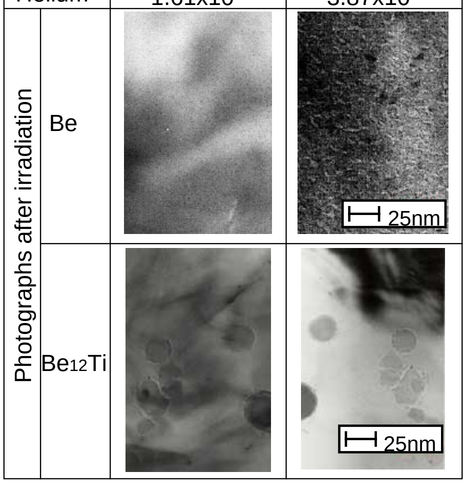


FIG. 6. Photographs of Be and $Be_{12}Ti$ after irradiation

3.1.5 Ion implantation

High He irradiation effects were preliminary evaluated by in-situ experiment using Multi Beam High Voltage Electron Microscope (MBHVEM) [9]. Helium ion and electron were irradiated at the same time. The fluences of He ion and electron were $3.87x10^{16}$ ions/m^2 and $2.86x10^{25}$ electrons/m^2, respectively. After the irradiation at room temperature, tiny bubbles and black dots were observed in pure Be specimens, however it was hard to observe the such irradiation defects in $Be_{12}Ti$ as shown in FIG. 6. $Be_{12}Ti$ had less irradiation defects formation than that of Be.

3.2 Fabrication technology of beryllides pebbles

After several studies, it became clear that the fabrication process and the chemical composition of the beryllides were critical for the brittleness and some beryllium contents gave better ductility [10]. Electrodes with some Be contents were sufficiently

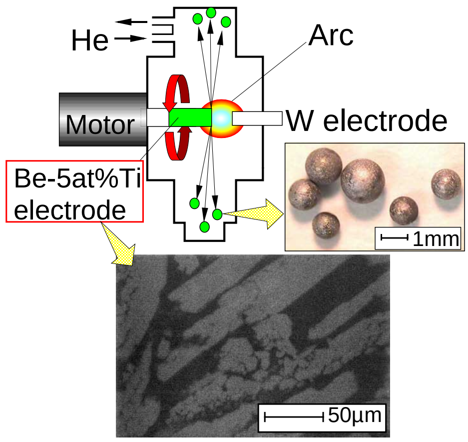


FIG. 7. Photographs of electrode and pebbles

ductile for the rotating electrode method and some pebbles were obtained (see FIG. 7).

4. Conclusion

The results of advanced blanket material development are as follows:
As to tritium breeder,

- Phase transformation at around 960˚C was not observed up to 10mol% TiO_2 doping.
- The effective thermal conductivity of TiO_2-doped Li_2TiO_3 pebble bed was within the design window.
- 5mol%TiO_2-doped Li_2TiO_3 pebbles with the target values were successfully fabricated by indirect wet process.

As to neutron multiplier,

- Compatibility of beryllide is smaller than that of Be.
- Swelling of beryllide is smaller than that of Be.
- Tritium inventory of beryllide is lower than that of Be.
- TBR using beryllide as a neutron multiplier is ensured the enough value.
- Irradiation defects of beryllide at high fluence irradiation are fewer than that of Be.
- Some prospects for ductility improvement of beryllide electrode were obtained.

From these activities, the advanced blanket materials with high temperature resistance have been successfully developed, and bright prospect was obtained to realize the DEMO blanket by the application of TiO_2-doped Li_2TiO_3 and beryllides.

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