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ITER-Test blanket module functional materials

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Abstract

Solid breeder and liquid breeder blanket concepts are being developed for testing in ITER. In addition to fundamental investigations on the use of reduced activation ferritic/ferritic–martensitic steels (RAFMS) or V-alloys as the structural material, tritium breeder and neutron multiplier materials, and corresponding corrosion issues, there are three classes of functional materials being developed. Performance of these functional materials will significantly impact the performance of respective blanket concepts. Two classes of materials are related to the self-cooled liquid breeder design concepts. The first class is MHD coatings for the self-cooled Li breeder concepts. The second class is for flow channel inserts (FCI) for the dual coolant PbLi concepts. The third class of functional material is tritium permeation barrier material commonly needed for solid and liquid breeder blanket concepts. A description and the development status of these functional materials are described in this paper.

1. Introduction

In the ITER-test blanket module (TBM) activity, solid breeder and liquid breeder blanket concepts are being developed for testing in ITER. During the assessment of different TBM concepts, many R&D items were identified, including basic development needs for different structural materials, solid breeders, and neutron multipliers. Performance limitations due to corrosion effects were also identified. These are presented in papers of this conference [1–3]. In addition to fundamental material R&D issues three classes of functional materials were identified. Performance of these functional materials will impact significantly the performance of different blanket concepts. Two classes of materials are related to the self-cooled liquid breeder design concept. The first class are magnetohydrodynamic (MHD) coatings like Er_2O_3 and Y_2O_3, which are proposed as the MHD insulation options required

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for the self-cooled Li breeder concept. The second class are for flow channel insert (FCI), such as SiC_f/SiC composite material being developed to perform the functions of MHD and thermal insulation for the dual coolant (DC) PbLi concepts. The third class of functional material is tritium permeation barrier (TPB) material, which will be needed to reduce the permeation loss of tritium to the environment for both solid breeder and PbLi concepts.

2. Liquid breeder TBM concepts

Liquid breeder TBM designs are proposed by different parties. The Russian Federation (RF) is proposing testing of a Li-self cooled TBM with Be as the neutron multiplier [4] to enhance the tritium breeding, and vanadium alloys as the structural material. Japan is considering the installation of liquid breeder TBMs such as Li-self cooled TBM without Be, or FLiBe-self cooled TBM in the later period of the ITER operation and testing [5]. The European Union (EU) is focusing on the helium-cooled PbLi concept (HCLL), where helium is used as the primary coolant to extract the blanket power. For higher thermal performance the US is proposing to test a dual coolant PbLi breeder concept (DCLL), where helium is used to cool all RAFMS structures, and the self-cooled breeder circulates slowly in order to reach a high exit temperature [6]. This concept is also proposed as a blanket option for the EU Power Plant Conceptual Study [7]. China is proposing to test blanket concepts called dual coolant PbLi (DLL) and single coolant PbLi (SLL), which are similar to the DCLL and HCLL concepts, respectively. For the DC designs FCIs are required as thermal and MHD insulators to separate the high temperature PbLi from the lower temperature RAFMS structures [8].

3. MHD coating design

For MHD coating, a thin ceramic coating on the inner surfaces of the channel wall has been proposed [9,10] for self-cooled designs to electrically decouple the flowing liquid metal and the wall to reduce the pressure drop and to limit the system pressure to an acceptable level.

3.1. MHD coating design requirements

The principal requirement for the coating, in addition to electrical resistivity, is compatibility between the flowing liquid metal and the substrate wall materials. In the case of liquid Li-self cooled blanket with vanadium structures, the highly reducing environment of Li narrows the option of candidate ceramics.

The requirements for the MHD insulator coating for Li/V blanket are [11]:

1. High electrical resistivity, with acceptable property change in the operating environment including radiation effects [12].
2. Chemical stability and compatibility with Li at the maximum operation temperature.
3. Mechanical integrity and thermal expansion match with V-alloy.
4. Safety/environmental characteristics, e.g. low activation.
5. Potential for coating on complex channel configurations.
6. Irradiation resistant.
7. In-situ self-healing of any defects that might occur.

3.2. MHD coating development

In Japan, the MHD insulator coating development has been enhanced by domestic programs and a Japan–US collaboration program (JUPITER-II) [13].

Previously, a CaO coating deposited by physical deposition or in-situ coating was one of the leading candidates. However, examination of the material coating showed that they have problems of stability in liquid Li at high temperature [14]. Efforts in recent years were focused on identifying new candidate materials that can withstand Li corrosion at high temperature.

Recently, Er_2O_3 and Y_2O_3, which were stable to 1073 K in liquid Li, were identified as promising candidate ceramics based on bulk immersion tests [14]. Feasibility of coating V–4Cr–4Ti with Er_2O_3 and Y_2O_3 was demonstrated by EB-PVD [15], Arc Source Plasma Deposition [16] and RF sputtering [17]. The crystalline Er_2O_3 coatings produced by Arc Source Plasma deposition were shown to be stable in Li to 1000 h at 800 °C [18].

Numerical estimates show that tolerable crack density of the coating could be very low [19]. These results encourage the development of double-layer coatings and revisiting of in-situ healing concepts. Double layers with V on Er_2O_3 showed satisfactory resistivity in molten Li to 600 °C [20]. The optimization of compatibility with Li is being investigated.

The in-situ coating method is an attractive technology because it could enable coating on complex surfaces after fabrication of the component and has the potential to heal cracks in the coating without the need to disassemble the component. In addition to physical deposition methods, in-situ coating with Er_2O_3 on V–4Cr–4Ti is being developed [21]. In this process, a thin insulating layer of Er_2O_3 is formed on V–4Cr–4Ti during its exposure to liquid Li by reaction of pre-charged oxygen in the vanadium alloy substrate and predoped Er in Li. Results showed significantly higher stability of the coating compared with the CaO in-situ coating.

Current focus in the RF is on multi-layer and double-layer coatings, where thin layers of insulating material are separated with thin layers of V–Cr–Ti [22]. Electrical insulation is provided by insulating layers, while the thin V–Cr–Ti layers would prevent lithium penetration into pores of the insulating material and damage its electro-insulating property. The concept was demonstrated in a number of experiments [22–25]. Present work is directed toward technology development on the deposition of electro-insulating and metallic layers and the selection of interface layers with good adhesion properties.

3.3. Flow channel insert design and requirements

For the dual coolant design, a SiC_f/SiC FCI is proposed as the MHD and thermal insulator. The feasibility of SiC_f/SiC FCIs for the DCLL design hinges on the compatibility of SiC_f/SiC with PbLi flow at temperatures approaching 800 °C (for a DEMO blanket) with characteristic impurities and thermal gradients leading to thermal stress loads in the insert. A SiC_f/SiC FCI must satisfy the following requirements:

- Chemically compatible with PbLi at temperatures up to ~800 °C in a flowing system and FS at lower temperatures (400–500 °C).
- Near 100% dense 'sealing layers' or alternate strategy, like double-layers, to avoid PbLi soaking into pores of the composite FCI.
- Resistance to high temperature gradients and primary stresses caused by normal and off-normal tokamak operation events like disruption.
- Irradiation resistance and acceptable changes in thermal and electrical conductivity, dimensional changes and structural integrity.
- Favorable safety/environmental characteristics, e.g. low activation.
- Fabrication to match flow channel geometry.

The requirements of low thermal (target ~2 W/m-K) and electrical conductivity (target range 1–50 S/m), especially in the direction normal to the wall, indicate that a simpler 2D weave should be considered. FCI electrical performance requirements go beyond the absolute value of the pressure in the channel, as changes in properties of the FCIs that lead to changes in the MHD pressure drop can also have large effects on the flow balance between parallel channels. This sensitivity to pressure drop means that moderate changes in FCI electrical resistance in one channel may lead to large differences in flow rate between parallel channels. Even if the overall pressure drop is acceptable, cracking and liquid metal penetrations have to be understood both from the material perspective and the subsequent impact on the liquid metal flow. This is a significant sensitivity issue for liquid metal blankets that has not been fully quantified.

3.4. FCI development

Advanced SiC_f/SiC appear to be radiation resistant at doses of ~10 dpa [26,27]. However, no experimental data exists for the design goal of 150–200 dpa for the fusion power reactor.

The study of the thermal conductivity of SiC_f/SiC composites has been significantly increased in recent years. Typical through-thickness non-irradiated thermal conductivity for chemically vapor-infiltrated (CVI) SiC–matrix composites with radiation-resistant SiC fibers at 500 °C is ~15 W/m-K [28,29]. Under neutron irradiation at the same temperature, the thermal conductivity decreases to a saturation value of 2–4 W/m-K at 1 dpa [28–30], which is in the range required for the FCI. Examples of measured and calculated thermal conductivity for non-irradiated and irradiated SiC_f/SiC are shown in Fig. 1, in which a negative temperature dependence of irradiated thermal conductivity is apparent.

The electrical conductivity for SiC_f/SiC is strongly affected by the matrix conductivity. In the fiber direction it is usually dominated by conduction through the carbon interphase [31,32]. Electrical conductivity of chemically vapor deposited or

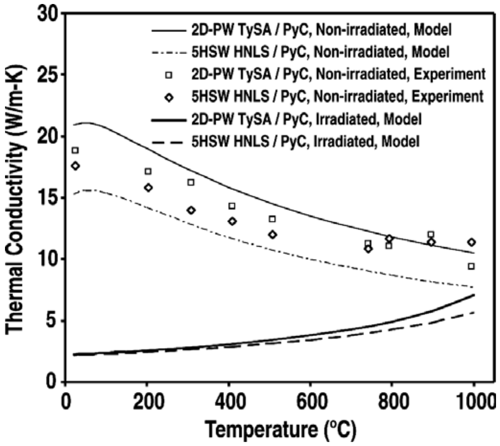

Fig. 1. Experimental and model-predicted temperature dependence of through-thickness thermal conductivity of 2D fusion-grade SiC_f/SiC composites. Note that conductivity of irradiated materials is that calculated at the irradiation temperature.

infiltrated SiC is most commonly determined by the nitrogen and other impurity concentrations, and typically has a range of 100–1000 S/m at 500 °C. A readily achievable through-thickness electrical conductivity for CVI SiC_f/SiC with impurity controlled matrix is in the range of 10–100 S/m. Fission neutron irradiation may increase or decrease the electrical conductivity. Minor changes have been reported at relatively low doses [30].

Although primary stresses on the FCI panel may be insignificant, through-thickness thermal stress could be substantial due to high temperature gradients. Furthermore, SiC develops a negative temperature dependent volumetric expansion under irradiation at temperatures below ~1000 °C [33]. Therefore, the internal stresses arise not only from thermal expansion but also from differential swelling, which could exceed typical matrix cracking stresses of CVI SiC_f/SiC depending on design parameters, state of mechanical constraint, and properties of the FCI itself.

FCI R&D is therefore directed toward material development and material/architectural design for low thermal and electrical conductivity while maintaining tolerance against through-thickness temperature gradients and neutron irradiation. The irradiation effect on the thermal conductivity of SiC_f/SiC is relatively well-addressed [28], whereas the effect on electrical conductivity of high-resistivity grade SiC is being studied in the HFIR 18J experiment [34]. For the assessment of mechanical integrity issues, the primary goal is to understand the irradiation creep of SiC and composites [35].

4. Tritium permeation barrier and requirements

The third class of functional material is the TPB material, which will be needed to reduce the permeation loss of tritium to the environment for both solid breeder and PbLi concepts. It is needed for PbLi breeder because of its low tritium solubility. The site release limit of tritium for a particular fusion reactor site will depend on the local regulation and presently is set for the ITER at 1 g/y (i.e. 27 Ci/d) [36]. The determination of a required tritium permeation reduction factor (PRF) to achieve this limit is a complex task which needs to take into account a number of factors, e.g. PbLi flow rate, efficiency of tritium extraction from PbLi and from He coolant, helium flow rate in the coolant purification system, design of a steam generator (SG), leak rate in the He coolant system. Presently, the target PRF for the EU HCLL breeder DEMO blanket components in contact with PbLi should be at least in the range of 10–50. In the SG, natural oxide based anti-permeation barriers should exhibit a PRF higher than 100 [37].

The requirements for the TPB are very similar to the MHD coating, but with different functions. The requirements for the TPB for solid and PbLi blankets are:

1. High tritium permeation resistance or PRF.
2. Chemical stability/compatibility with adjacent environment like He or PbLi at operating temperatures, thermal cycle and environment.
3. Mechanical integrity/thermal expansion matches with the substrate material and crack resistant.
4. Irradiation resistance.
5. Safety/environmental characteristics, e.g. low activation.
6. Potential for coating on complex internal or external channel configurations.
7. Potential for in-situ self-healing of any defects that might occur.

4.1. Development in the EU

The design of the EU HCLL DEMO breeder blanket incorporates a TPB on the blanket module surfaces in order to limit tritium permeation into the Helium Coolant System. The performance of such TPB should be tested in the respective ITER TBM. Aluminum rich coatings forming Al_2O_3 at the surface were studied for several years as TPB in the European Fusion Technology Program [38].

Hot-dip aluminization (HDA) [39–41], chemical vapor deposition (CVD) [42] and physical vapor deposition (PVD) [43] are being used as deposition techniques. In the HDA process [39–41] the RAFM steel EUROFER to be coated is dipped into liquid Al, heated up to 700 °C for 30 s, and cooled down in an Ar–5%H_2 atmosphere. Afterwards the standard heat treatment of EUROFER is applied. The microstructure of the coated layer consists of an outer FeAl layer and an inner α-Fe(Al) phase. Overall thickness of the layer is about 120–150 μm.

The CVD process is performed in two steps [42]:

- Deposition of FeAl layer by pack-cementation.
- Deposition of Al_2O_3 on top by metal-organic CVD method.

A 1 μm thick crystalline alumina α-Al_2O_3 coating is produced on the substrate surface by a PVD process [43]. The deposition is performed by an arc discharge using an aluminum cathode, filtering metal droplets from the plasma and introducing oxygen into the main chamber. The HDA and CVD aluminum coatings on EUROFER were tested in ENEA-Brasimone in hydrogen gas and in Pb–15.7Li alloy [44]. The measured PRFs did by far not fulfill the requirements. SEM examinations showed detachment of the coatings and cracks, therefore R&D effort is still needed.

Experiments on deuterium permeation through EUROFER coated by α-alumina were performed by IPP Garching [43]. The permeation tests with coated and uncoated EUROFER specimens were done in the temperature range of 300–600 °C at pressures of 10^3–10^5 Pa, but the temperatures of the coated samples had to be chosen higher (up to 800 °C) to enable detection of permeated deuterium with the available quadrupole mass spectrometry (QMS). The measured PRF is 10^3 or even higher. In addition to the very good permeation results the α-alumina layer demonstrated a high structural stability with respect to thermal cycles up to 800 °C.

The main directions in the development of suitable anti-permeation coatings in the EU are as follows:

- Development of AlFe-based anti-permeation coatings and of W anti-corrosion coatings.
- Development of new advanced coating processes (e.g., galvanic deposition of aluminum, electro-spark deposition, CVD).
- Qualification of the developed coatings.
- Development of natural oxide based anti-permeation barriers on the SG Inconel/Incoloy inner surfaces Determination of proper He coolant conditioning (e.g. ratio of hydrogen and water vapor) in order to achieve thermo-mechanical stability and required PRF.

5. Conclusions

Three classes of functional materials have been identified. Performance of these materials is crucial to the performance of TBM concepts being developed to be tested in ITER. They are the MHD coatings, FCI and TPB. Design requirements of these functional materials have been identified. Possible material options have also been identified. Intense R&D efforts in Japan, EU, RF and the US have been initiated. Some encouraging results have been obtained, but these developments are still in their infancy. In addition to basic performance, critical uncertainties are also in the area of irradiation effects and corresponding material property changes. With the common interest in the development of similar blanket concepts among ITER participant nations, increased effort, collaboration and coordination in this area of development are encouraged and expected. ITER will provide a necessary integrated testing environment, but due to ITER's limited fluence capability, independent fusion spectrum testing facilities like the IFMIF and Components Testing Facility (CTF) will be needed.

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References

[1] D. Gelles, S. Jitsukawa, A. Kimura, R. Klueh, G. Odette, B. van der Schaaf, J. Nucl. Mater., these Proceedings, doi:10.1016/j.jnucmat.2007.03.067.

[2] T. Muroga, J.M. Chen, V.M. Chernov, K. Fukumoto, D.T. Hoelzer, R.J. Kurtz, T. Nagasaka, B.A. Pint, M. Satou, A. Suzuki, H. Watanabe, J. Nucl. Mater., these Proceedings, doi:10.1016/j.jnucmat.2007.03.082.

[3] V.M. Chernov, M.V. Leonteva-Smirnova, M.M. Potapenko, V.R. Barabash, D.T. Hoelzer, R.L. Klueh, R. Kurtz, S. Zinkle, E. Diegele, R. Laesser, R. Lindau, E. Lucon, A. Moeslang, M. Rieth, B. van der Schaaf, T. Muroga, S.

Jitsukawa, C. Pan, Y. Wu, these Proceedings, doi:10.1016/j.jnucmat.2007.03.115.
[4] I.R. Kirillov, G.E. Shatalov, Y.S. Strebkov, Fus. Eng. Design 81 (2006) 425.
[5] M. Enoeda, M. Akiba, S. Tanaka, A. Shimizu, A. Hasegawa, S. Konishi, A. Kimura, A. Kohyama, A. Sagara, T. Muroga, Fus. Sci. Technol. 47 (2005) 1023.
[6] C.P.C. Wong, S. Malang, M. Sawan et al., Fus. Eng. Design 81 (2006) 461.
[7] D. Maisonnier et al., A conceptual study of commercial fusion power plants, report EFDA-RP-RE-5.0, April 2005.
[8] N.B. Morley, S. Malang, I. Kirillov, Fus. Sci. Technol. 47 (2005) 488.
[9] D.L. Smith, J. Konys, T. Muroga, V. Evitkhin, J. Nucl. Mater. 307–311 (2002) 1314.
[10] B.A. Pint, P.F. Tortorelli, A. Jankowski, J. Hayes, T. Muroga, A. Suzuki, O.I. Yeliseyeva, V.M. Chernov, J. Nucl. Mater. 329–333 (2004) 119.
[11] D.L. Smith, J.H. Park, K. Natesan, J. Nucl. Mater. 307–311 (2002) 1405.
[12] V.M. Chernov, V.A. Belyakov, A.M. Bryuzgin, et al., J. Nucl. Mater. 233–237 (1996) 1304.
[13] <http://jupiter2.iae.kyoto-u.ac.jp/index.html>.
[14] B.A. Pint, L.D. Chitwood, J.R. Di Stefano, J. Nucl. Mater. 289 (2001) 52.
[15] B. Pint, P.F. Tortorelli, A. Jankowski, J. Hayes, T. Muroga, A. Suzuki, O.I. Yeliseyeva, V.M. Chernov, J. Nucl. Mater. 329–333 (2004) 119.
[16] F. Koch, R. Brill, H. Maier, D. Levchuk, A. Suzuki, T. Muroga, H. Bolt, J. Nucl. Mater. 329–333 (2004) 1403.
[17] A. Sawada, A. Suzuki, B. Pint, T. Terai, T. Muroga, Fus. Eng. Design 81 (2006) 579.
[18] A. Sawada, B.A. Pint, A. Suzuki, F. Koch, H. Maier, T. Terai, T. Muroga, J. Nucl. Mater., these Proceedings.
[19] H. Hashizume, Fus. Eng. Design 81 (2006) 1431.
[20] B.A. Pint, J.L. Moser, A. Jankowski, J. Hayes, J. Nucl. Mater., these Proceedings, doi:10.1016/j.jnucmat.2007.03.208.
[21] Z. Yao, A. Suzuki, T. Muroga, K. Katahira, J. Nucl. Mater. 329–333 (2004) 1414.
[22] I.R. Kirillov, N.D. Kraev, V.P. Ostapenko, A.E. Rusanov, I.V. Vitkovsky, in: Proceedings of First International Workshop on Liquid Metal Blanket Experimental Activities, Paris, France, September 16–18, 1997.
[23] L. Barleon, V. Casal, L. Lenart, Fus. Eng. Design 14 (1991) 401.
[24] I.A. Evtushenko, I.R. Kirillov, S.I. Sidorenkov, C.B. Reed, in: Proceedings of the Second International Conferences on Energy Transfer in Magnetohydrodynamic Flows, Aussois, France, September 26–30, 1994.
[25] FZKA Report 6966, October 2002–September 2003.
[26] Y. Katoh, L.L. Snead, C.H. Henager, Jr., A. Hasegawa, A. Kohyama, B. Riccardi, H. Hegeman, J. Nucl. Mater., these Proceedings, doi:10.1016/j.jnucmat.2007.03.032.
[27] Y. Katoh, T. Nozawa, L.L. Snead, T. Hinoki, J. Nucl. Mater., these Proceedings, doi:10.1016/j.jnucmat.2007.03.083.
[28] Y. Katoh, T. Nozawa, L.L. Snead, T. Hinoki, A. Kohyama, Fus. Eng. Design 81 (2006) 937.
[29] G.E. Youngblood, D.J. Senor, R.H. Jones, J. Nucl. Mater. 329–333 (2004) 507.
[30] L.L. Snead, S.J. Zinkle, D.P. White, J. Nucl. Mater. 340 (2005) 187.
[31] L.L. Snead, J. Nucl. Mater. 329–333 (2004) 524.
[32] R. Scholz, F. Dos Santos Marques, B. Riccardi, J. Nucl. Mater. 307–311 (2002) 1098.
[33] Y. Katoh, H. Kishimoto, A. Kohyama, J. Nucl. Mater. 307–311 (2002) 1221.
[34] Y. Katoh, A. Hasegawa, T. Hinoki, A. Kohyama, in: Sixth IEA International Workshop on SiC/SiC Ceramic Composites for Fusion Applications, June 10–11, 2004, Boston, p. 160.
[35] Y. Katoh, L.L. Snead, J. Nucl. Mater., these Proceedings.
[36] W. Farabolini, A. Ciampichetti, M.A. Fütterer, L. Giancarli, G. Laffont, A. Li Puma, S. Raboin, Y. Poitevin, I. Ricapito, P. Sardain, Fus. Eng. Design 81 (2006) 469.
[37] M. Fütterer, X. Raepsaet, E. Proust, Fus. Engin. Design 29 (1995) 225.
[38] J. Konys, A. Aiello, G. Benamati, L. Giancarli, Fus. Sci. Technol. 47 (2005) 844.
[39] H. Glasbrener, J. Konys, G. Reimann, K. Stein, O. Wedemeyer, in: Proceedings of the 19th Symposium on Fusion Technology, Lisbon, Portugal, September 16–20, 1996.
[40] H. Glasbrener, O. Wedemeyer, J. Nucl. Mater 257 (1998) 274.
[41] H. Glasbrener, J. Konys, J. Nucl. Mater. 58&59 (2001) 725.
[42] C. Chabrol, F. Schuster, E. Serra, G. Le Marois, in: Proceedings of the 20th Symposium on Fusion Technology, Marseille, France, September 7–11, 1998.
[43] D. Levchuk, F. Koch, H. Maier, H. Bolt, J. Nucl. Mater. 328 (2004) 103.
[44] A. Ailello, I. Ricapito, G. Benamati, A. Ciampichetti, Fus. Eng. Design 69 (2003) 245.