Fusion Engineering and Design 85 (2010) 1824–1828

Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

Electrical insulation test of alumina coating fabricated by sol–gel method in molten PbLi pool

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ARTICLE INFO

Article history:
Available online 15 July 2010

Keywords:
Electrical insulation coating
Alumina
Sol–gel method
Lead–lithium

ABSTRACT

Development of electrical insulation coatings, which insulate an induced electric current from electrical conducting walls, is a key technology for the research and development of self-cooled liquid metal blanket including lead–lithium (PbLi) fusion blankets. As for magnetohydrodynamic (MHD) thermofluid study, an electrical insulation coating is extremely important from the viewpoint of the secure electrical insulating wall condition. The present study employs a sol–gel (SG) method to fabricate an Al_2O_3 coating, and discusses the feasibility of the SG coating as an electrical insulation coating for the PbLi through the electrical insulation test in the molten PbLi pool and the SEM with EDS analysis on the SG coating structure. The present study shows that the SG coating will be a potential electrical insulation coating for PbLi with both the operation time and the temperature limitation.

1. Introduction

A liquid metal flow in a strong magnetic field **B** induces an electric current **J**, and then interacts with **B**. As a result, the Lorentz force, $\mathbf{J} \times \mathbf{B}$ dominates the liquid metal flow under the strong magnetic field. The heat and mass transfers of the liquid metal flow under the strong magnetic field are also significantly affected by the Lorentz force, known as a magnetohydrodynamic (MHD) effect. The MHD thermofluid regime is determined by not only hydrodynamic and thermal conditions but also electric boundary conditions. A MHD duct flow confined by electrical conducting walls experiences a significant increase in pressure drop, known as MHD pressure drop.

Development of electrical insulation coatings, which insulate an induced electric current from electrical conducting walls, is a key technology for the research and development of self-cooled liquid metal blanket including lead–lithium (PbLi) fusion blankets [1]. As for MHD thermofluid study, an electrical insulation coating is extremely important from the viewpoint of the secure electrical insulating wall condition.

The dual-functional lead–lithium (DFLL) concept adopts two optional concepts of PbLi blankets including the reduced activation ferritic/martensitic (RAFM) steel-structured Helium-cooled quasi-static PbLi tritium breeder (SLL) blanket and the RAFM steel-structured Helium-gas/PbLi dual-cooled (DLL) blanket. DFLL concept considers an alumina (Al_2O_3) as a candidate for the electrical insulation coating against PbLi flows for the DLL blanket. The DFLL blanket concept employs a hot dip aluminizing (HDA) process, chemical vapor deposition (CVD) [2], or atmospheric plasma spray (APS) [3] to fabricate Al_2O_3 coatings on the RAFM steels. There are other purposes of coatings in fusion reactor blankets, depending on fusion blanket concepts. The water-cooled PbLi breeder (WCLL) concept with ferritic steel structures [4] adopts an Al_2O_3 coating as tritium permeation barrier (TPB) in order to reduce the tritium permeation into the water coolant caused by relatively high tritium partial pressure produced in the PbLi breeder to an acceptable level. In addition to the TPB, Al_2O_3 coatings have been studied as PbLi corrosion barrier because the PbLi solubility of Fe, Cr and particularly Ni are much higher than molten Li, resulting in greater dissolution than Li [5,6].

Most efforts of the Al_2O_3 coating development focus on fabricating an Al_2O_3 coating on ferritic/martensitic steels by means of HDA process [7], CVD [8], vacuum plasma spray (VPS) [9], low pressure plasma spray (LPPS) and APS [10]. The above investigations are originally not oriented for the Al_2O_3 electrical insulation coating against PbLi flows, but for the coating as TPB and corrosion barrier. Nevertheless, they are informative for the Al_2O_3 coating as electrical insulation coating in terms of the Al_2O_3 coating compatibility with the molten PbLi [11,12].

There are considerable requirements that must be satisfied in the coating for the fusion application. General requirements of coatings used for all fusion system are summarized as follows [1]:

(1) Potential for coating large complex geometry or configuration,

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doi:10.1016/j.fusengdes.2010.06.004

(2) potential for in situ self-healing of defects that might occur,
(3) processing parameters should be compatible with material and capabilities, e.g. temperatures and processing durations,
(4) bonding/thermal expansion should match with substrate,
(5) acceptable neutronic properties,
(6) material availability/cost,
(7) safety/environmental characteristics, and
(8) radiation damage resistance.

In addition, electrical insulation coatings are required to have sufficient insulation efficiency. An electrical insulation efficiency of coatings is generally evaluated by the product of coating electric resistivity ρ_i and coating thickness δ_i, called as coating resistance $\rho_i\delta_i$. A previous study has estimated 10 μm thickness of an Al_2O_3, which has an electric resistivity $\rho_i \sim 10^{10}\ \Omega$ m at 400 °C, yields the almost perfect electrical insulation with $\rho_i\delta_i = 10^5\ \Omega\,m^2$ [13]. For the MHD thermofluid studies, some coating requirements may be eased because the thermofluid studies require a secure electrical insulation wall condition without neutron irradiation just for the experiment time period, which is much shorter compared to a time period of the fusion reactor operation.

The Al_2O_3 coatings fabricated on RAFM steels by HDA process and VPS have the favorable adhesion to its substrate even after being exposed in molten PbLi. However, the fabrication techniques are, in general, high cost and it is hard to fabricate the coatings on a large complex configuration. The present study employs a sol–gel (SG) method to fabricate an Al_2O_3 coating. The SG method is a wet-chemical technique used for fabricating ceramic materials, and it has the following advantages:

(1) Easy material availability,
(2) easy process to fabricate the Al_2O_3 coating on a substrate,
(3) applicable to large complex configurations, and
(4) low cost fabricating process.

On the other hand, the SG coating has poor adhesion to its substrate compared to the other processes such as HDA process.

The present study focuses on the Al_2O_3 coatings fabricated by SG method and discusses the feasibility that the SG coating works as electrical insulation coating for the purpose of PbLi MHD flow experiments, where the PbLi operation temperature is relatively lower, the PbLi exposure time is shorter compared to the fusion blanket operation, and the neutron irradiation is not applied.

2. Al_2O_3 coating by sol–gel method

The present study employs a commercial SG coating material: Ceramacoat™ 503-VFG-C (The Armco Products, Inc). The Ceramacoat™ is a single-component, Al_2O_3-filled, high-temperature (maximum durable temperature: 1650 °C), and electrical insulation coating material. The Ceramacoat™ contains Al_2O_3 and mono aluminum phosphate ($AlPO_4$) suspended in an inorganic binder system. The cured Al_2O_3 coating is $10^7\ \Omega$ m at room temperature in volume resistivity.

2.1. Coating fabrication

The SG coating hardly gets enough adhesion to a smooth-surface substrate after curing. Substrate surfaces are roughened and cleaned using a surface cleaner in order to remove mechanical oil leftovers before applying the Al_2O_3 coating material. Then, the Al_2O_3 coating material is applied to the surface-prepared substrates in a thin coat using a brush to maintain a uniform material thickness. The coating applied substrates are dried in the air for about 4 h at room temperature, then cured at 95 °C, 260 °C and 370 °C for 2 h at each temperature sing electric furnace. In the curing process, a rapid increase temperature of the coatings may cause a rapid evaporation of the coating binder. As results, some coating cracks and peelings might occur. Therefore we employed the step curing to avoid the effect by following the coating company instructions.

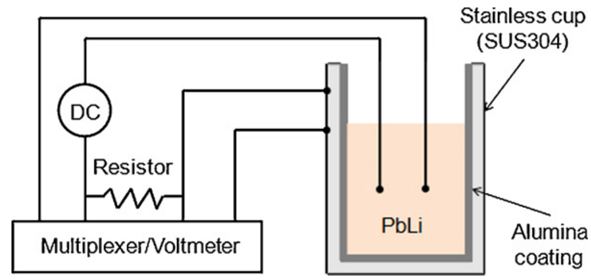

Fig. 1. Electrical insulation test.

3. Electrical insulating test of the Al_2O_3 coating in a PbLi pool

There are considerable studies performed on coating issues. However, attentions have been paid mainly to coating fabrication techniques, the tritium permeation and corrosion behaviors through morphology of the corrosion layers and discussions on chemical reactions between the liquid metal and wall material [11,12,14].

There is no research on electric insulation performance of the coatings in contact with liquid metal. The SG coating is expected to be less durable against thermal expansion differences because the SG coating has poor adhesion. An electrical insulation test of the SG coating in a PbLi pool was carried out to discuss the electrical insulation performance in contact with the molten PbLi, and then discuss the feasibility of the SG coating as electrical insulation coating for MHD thermofluid research.

3.1. Experimental setup

Electrical insulating tests in a molten PbLi pool were performed to examine an electrical insulating performance of the Al_2O_3 coating fabricated by the SG method. The SG coatings were fabricated on SUS304 cups used in the test by going through the above-mentioned procedure. Fig. 1 shows the setup of the electrical insulating test. The Al_2O_3-coated cups were filled with the molten PbLi in an electric furnace. One side of electrodes was attached to the cup substrate, and the other side of electrodes was immersed in the molten PbLi. The electrodes were connected to a power supply to apply a few volts on them. They were also connected to a multiplexer to measure an electric current passing through the SG coating with time variation. The PbLi temperature, the air temperature in the electric furnace and the electric current passing through the SG coating were measured every 10 min by the multiplexer. The following two kinds of test runs were conducted;

Run #1: molten PbLi temperature was at 300 °C for around 170 h. (Isothermal)
Run #2: molten PbLi temperature was increased from 300 °C up to 500 °C. (Heating-up test)

In a design of PbLi blanket, it is proposed to operate at higher temperature. However, the present study is primarily oriented for the PbLi MHD thermofluid. The experiment temperatures were determined from a viewpoint of keeping the PbLi melt during experiments. The PbLi melting temperature is 235 °C. The present temperature range (around 300–500 °C) is high enough for the PbLi