Characterization and thermomechanical assessment of a SiC-sandwich material for Flow Channel Inserts in DCLL blankets

Preprint of Paper to be submitted for publication in Proceeding of 30th Symposium on Fusion Technology (SOFT)

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.
Characterization and thermomechanical assessment of a SiC-sandwich material for Flow Channel Inserts in DCLL blankets

C. Soto\textsuperscript{a,b}, C. García-Rosales\textsuperscript{a,b}, J. Echeberria\textsuperscript{a,b}, E. Platac\textsuperscript{c}, A. Shisko\textsuperscript{c}, F. Muktepavela\textsuperscript{c}, M. Malo\textsuperscript{d}, T. Hernández\textsuperscript{d}

\textsuperscript{a}Ceit-IK4, E-20018 San Sebastian, Spain
\textsuperscript{b}Universidad de Navarra, Tecnun, E-20018 San Sebastian, Spain
\textsuperscript{c}Institute of Physics, University of Latvia, Salaspils 2169, Latvia
\textsuperscript{d}CIEMAT, National Fusion Laboratory, 28040 Madrid, Spain

Flow Channel Inserts (FCIs) are key elements in the high-temperature Dual Coolant Lead Lihium (DCLL) blanket, since they insulate electrically the flowing PbLi to avoid MHD effects and protect the steel structure from the hot liquid metal. SiC-based materials are main candidates for high-temperature FCIs, being a dense-porous SiC-based sandwich material an attractive option. The present work is focused on the development of such a SiC-based material.

On the one hand, in order to assess the suitability of the concept for FCIs, the main results of a stress analysis, MHD and heat transfer simulations are summarized. On the second hand, the experimental production of the SiC-based material is addressed, where the porous SiC core is manufactured from SiC powder by two different techniques, uniaxial pressing and gelcasting. The porosity is introduced using graphite spherical powder as a sacrificial template. After the production of the porous SiC core, a dense SiC coating of \( \sim 200 \, \mu m \) thickness is deposited by CVD, being its response tested against hot PbLi in corrosion experiments. The properties of the material in terms of thermal and electrical conductivities, flexural strength and elastic modulus were measured, with promising results for high-temperature FCIs.

1. Introduction: high-temperature DCLL and Flow Channel Inserts

The Dual Coolant Lead Lithium (DCLL) blanket is one of the concepts being developed in the EU framework as a candidate for a future fusion reactor [1]. This design is characterized by the use of liquid PbLi both as main coolant and breeder, which is flowing through poloidal channels at velocities of \( \sim 10 \, \text{cm/s} \) while heating up due to the neutron flux [2]. In the high-temperature approach of the DCLL, the liquid metal (LM) reaches temperatures up to \( \sim 700 \, ^\circ C \), leading to potentially high efficiencies.

Due to the relative movement between the conducting LM and the high toroidal magnetic field, electric currents are generated in the fluid domain, whose associated Lorentz forces interact with the flow causing a pressure drop and potential alterations in its velocity and temperature fields. For this reason, a major issue in the DCLL blanket is to provide electrical insulation for the PbLi in the poloidal channels. At the same time, thermal insulation is needed to protect the blanket steel structure from the high temperatures of the LM. To develop a near-term DCLL avoiding this last issue, a low-temperature DCLL design was carried out in CIEMAT, achieving substantial progresses in terms of efficiency, TBR, and tritium extraction [3][4][5].

The above tasks are carried out by the so-called Flow Channel Inserts (FCIs), usually conceived as hollow channels of a few mm thickness containing the PbLi within the blanket structure. Apart from providing the required electrical and thermal insulation, FCIs should provide adequate response against hot flowing PbLi, together with enough mechanical integrity to withstand the thermally-derived stresses associated to the high thermal gradient across the channel’s walls. For this reasons, SiC-based materials are considered as main candidates for high-temperature FCIs, being one of the possible approaches to develop a dense-porous SiC-based sandwich material with adequate properties. In this material, an outer CVD-SiC dense coating provides the protection against PbLi corrosion and infiltration, while a porous SiC core provides the proper insulation.

2. Requirements for the SiC-based sandwich material: computer simulations

2.1 Thermally-derived stresses

A considerably high thermal gradient (of \( \sim 100-200 \, ^\circ C \)) will be present across the FCIs walls due to the
thermal insulation. Even if further geometrical constraints are not considered in the mechanical analysis of the poloidal FCIs (conceiving them as long channels directly immersed in PbLi [2]), the thermally-derived stresses associated to this gradient can be considerably high. In order to assure the mechanical safety of the component, the value of the stresses were studied by FEM simulations, performed with the software ABAQUS; more details of the model used can be found in [6].

With the assumptions considered, the value of the thermally-derived stresses depends mainly on the thermal gradient across the FCI (\(\Delta T_{FCI}\)), on the thickness of the dense layer of the SiC-sandwich (\(\delta_{dense}\)) and on the elastic properties of the porous SiC core (\(E_{porous}\)). \(\Delta T_{FCI}\) is related to the thermal conductivity and thickness of the core, \(k_{porous}\) and \(\delta_{porous}\). To offer a guideline for the stress range expected in the FCI during blanket operation, in table 1 the maximum stresses present in the dense and porous SiC layers are shown, as a function of \(\Delta T_{FCI}\), if \(k_{porous}\) is 10 W/(m·K), \(\delta_{dense}\) is 200 µm and \(E_{porous}\) is 120 GPa.

For a fixed \(\Delta T_{FCI}\), the thermally-derived stresses are reduced if relatively thin dense coatings are considered (\(\delta_{dense} < 1 \text{ mm}\)) and if the use of a highly porous material (\(k_{porous} \approx 5 \text{ W/(m·K)}\)) is avoided in the sandwich core [7].

<table>
<thead>
<tr>
<th></th>
<th>(\Delta T_{FCI} = 120 \degree \text{C})</th>
<th>(\Delta T_{FCI} = 200 \degree \text{C})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Porous SiC</td>
<td>45</td>
<td>69</td>
</tr>
<tr>
<td>Dense SiC</td>
<td>50</td>
<td>145</td>
</tr>
</tbody>
</table>

Table 1. Maximum stresses predicted in the porous and dense SiC layers, as a function of the thermal gradient across the FCI (\(k_{porous} = 10 \text{ W/(m·K)}\); \(\delta_{dense} = 200 \mu\text{m}\); \(E_{porous} = 120 \text{ GPa}\)).

### 2.2 MHD effects

The interaction between the flowing PbLi and the magnetic field may cause the alteration of the flow due to MHD effects, which are strongly dependent on the electrical conductivity of the FCI. If the channel is not properly insulated, a high pressure drop is registered in the bulk PbLi; at the same time, the velocity profile of the LM bulk may be altered due to the formation of high-velocity jets near the side walls. The flow in the gap between the FCI and the steel structure, filled with PbLi, may be also affected [8]. The MHD effects were studied by simulations using ANSYS-Fluent.

The pressure drop reduction factor (\(R\), ratio between the pressure drop without and with the FCI) as a function of the FCI electrical conductivity is shown in fig. 2 for a 4 T field. As can be observed, the bulk PbLi can be considered as properly insulated if a material with an electrical conductivity below ~1 S/m is used for FCIs. The pressure drop in this case is reduced to ~123 Pa/m, in comparison to the ~59 MPa/m without the FCI.

As an example of the results obtained ([7], to be published), the velocity profile in the channel cross-section if an insulating FCI is considered is shown in fig. 3. The bulk PbLi presents a flatter velocity profile due to the effect of the Lorentz forces; in the side gap, the velocity is considerably lower than in the bulk, being almost stagnant in the Hartmann gap.

A parametric study concerning the influence of the dense coating on MHD effects was obtained in [7]. As a main conclusion it can be asserted that, if a dense CVD-SiC coating is considered (whose electrical conductivity is expected to be < 500 S/m [9]) and if the thickness of the coating is kept < 1 mm, its effect on pressure drop and velocity profile is negligible for the blanket performance.

### 2.3 Heat transfer

To accurately predict the temperature field in the blanket the actual PbLi velocity profile must be considered, together with the volumetric heating due to the neutron flux, whose intensity decreases exponentially with the distance from the first wall [10][11]. To this effect, a heat transfer analysis was performed in ANSYS-Fluent considering a poloidal channel of 2 m length; to simulate the neutron flux, an exponential heat source term was applied to the system, with a maximum located at the outer steel wall. The inlet PbLi temperature was 460 °C [2][11].

As a summary of the results obtained, if the thermal conductivity of the porous SiC is 10 W/(m·K) and an electrically insulating FCI is considered, the main temperatures of the temperature field are summarized in table 2. The temperature map in the poloidal channel and in the outlet cross-section in this case is shown in fig. 4.

<table>
<thead>
<tr>
<th></th>
<th>(\Delta T_{FCI})</th>
<th>(T_{max, \text{ bulk PbLi}})</th>
<th>(T_{max, \text{ steel}})</th>
<th>(T_{max, \text{ FCI}})</th>
<th>(T_{max, \text{ front gap}})</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>116 °C</td>
<td>678 °C</td>
<td>536 °C</td>
<td>628 °C</td>
<td>562 °C</td>
</tr>
</tbody>
</table>

Table 2. Main temperatures of the temperature field considering an insulating FCI of 10 W/(m·K)
To assure the safety of the blanket avoiding corrosion issues, the temperature in the steel-PbLi interface is recommended to be \(<470\) °C \([2][12][13]\). According to the above results, the front gap can be identified as a possible trouble point in the high-temperature DCLL, since it is subjected to a high intensity heating due to neutrons but it is not thermally insulated by the FCI as the bulk PbLi.

3. Fabrication and characterization of the SiC-based material

From the theoretical analysis previously presented, an optimal range of properties for FCIs can be deduced. To produce an adequate material, a powder metallurgical route to fabricate porous SiC was developed, introducing the porosity by using graphite spherical powder as a sacrificial phase. The details concerning the fabrication route are described in \([14]\) and \([15]\).

Two techniques were used to conform the samples: uniaxial pressing and gelcasting. Porous SiC materials with porosities between 35 and 50% were produced by uniaxial pressing; as an example, the microstructure of a \(~40\)% porous material is shown in fig. 5. Together with the materials fabricated by uniaxial pressing, the adaptation of the production route to the gelcasting technique (a promising method to produce complex geometries) was explored. The first samples were fabricated, and even though further work is required to optimize the route, their properties were comparable to those of the uniaxially-pressed materials. A picture of the first hollow porous SiC channels produced by gelcasting is shown in fig. 6.

As a summary of the characterization performed, the properties of a \(~40\)% porous material are shown in table 3. As can be deduced by comparing the results with the requirements marked by the theoretical discussion, such a material is promising for the core of SiC-based sandwich FCIs. It should be mentioned that the flexural strength of the CVD-SiC is well above the one of porous SiC \([16]\).
4. Response of dense CVD-SiC against hot PbLi

The response of a 200 µm coating against PbLi was measured in corrosion experiments. Flat samples fabricated by uniaxial pressing were tested both against hot static PbLi at 700 °C and flowing at ~10 cm/s and 550 °C (for 1000 h); no remarkable signs of corrosion or PbLi infiltration were found after the experiment.

Hollow SiC samples fabricated by gelcasting were also tested against flowing PbLi; in this experiment, however, unexpected failures during the experiment provoked the breakup of three of four of the samples tested, despite the good response of the coating observed after the test. Failures must be avoided in future experiments, and the quality of the porous SiC channels should be improved. A picture of some of the samples after the corrosion experiments against flowing PbLi is shown in fig. 9.

5. Conclusions

A dense-porous SiC-based sandwich material represents a promising option for Flow Channel Inserts in a high-temperature DCLL blanket. With the production route developed, porous SiC was successfully fabricated with a wide range of porosities and properties. According to the theoretical analysis performed, a ~40% porous material presents promising properties for the porous SiC core of the sandwich. A 200 µm CVD-SiC coating offers a good response against hot PbLi, although further experiments must be done testing the response of hollow FCI prototypes.

6. Acknowledgments

This work has been carried out within the framework of the EUROFusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Table 3. Properties measured in a ~40% porous SiC

<table>
<thead>
<tr>
<th>k_{porous} (W/(m·K))</th>
<th>~10 W/m·K</th>
</tr>
</thead>
<tbody>
<tr>
<td>σ_{porous} (S/m)</td>
<td>&lt; 1 S/m</td>
</tr>
<tr>
<td>E_{porous} (GPa)</td>
<td>118 GPa</td>
</tr>
<tr>
<td>Flexural strength (MPa)</td>
<td>80 ± 5 MPa</td>
</tr>
</tbody>
</table>

7. References