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

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Flow Channel Inserts (FCIs) are key elements in the high-temperature Dual Coolant Lead Lithium (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 other 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 ~200 μm thickness is deposited by Chemical Vapor Deposition (CVD); the coated material was 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. The PbLi flows through poloidal channels at velocities of ~10 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 ~700 °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. On order 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-mentioned 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 potential corrosion issues due to hot flowing PbLi, together with enough mechanical integrity to withstand the thermally-derived stresses associated to the high thermal gradient across the walls of the channel. 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.

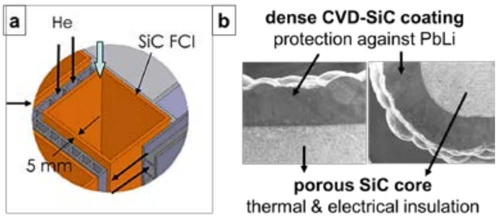

Fig.1. a) Location of the Flow Channel Inserts in the DCLL blanket [2]; b) Microstructure of a dense-porous SiC-based sandwich material for FCIs

In this work, the development of a SiC-based material for high-temperature FCIs is presented. On the one hand, the suitability of the material for FCIs was analyzed by numerical simulations, discussing the adequate range of properties for the material together with the optimum configuration of the sandwich. In parallel, the fabrication of a SiC-based material with the required properties was carried out, developing a production route for porous SiC and characterizing the resulting material in terms of thermal and electrical conductivities, flexural strength, and elastic modulus. The response of a CVD-SiC coating against PbLi was tested in corrosion experiments.

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

- **Thermally-derived stresses**

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A considerably high thermal gradient (of ~100-200 °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 depend mainly on the thermal gradient across the FCI (ΔT_{FCI}), on the thickness of the dense layer of the SiC-sandwich (δ_{dense}) and on the elastic properties of the porous SiC core (E_{porous}). ΔT_{FCI} is related to the thermal conductivity and thickness of the core, k_{porous} and δ_{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 ΔT_{FCI}, if k_{porous} is 10 W/(m·K), δ_{dense} is 200 µm and E_{porous} is 120 GPa.

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

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 W/(m·K); δ_{dense}= 200 µm; E_{porous} = 120 GPa)

	Maximum stress (MPa)	
	ΔT_{FCI} = 120 °C	ΔT_{FCI} = 200 °C
Porous SiC	45	69
Dense SiC	50	145

▪ 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 flattered 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.

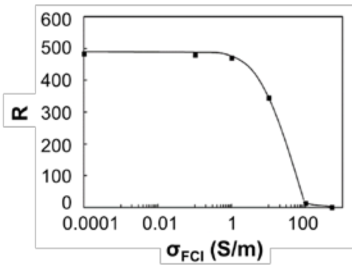

Fig. 2. Pressure drop reduction factor (R) as a function of the electrical conductivity of the FCI (σ_{FCI})

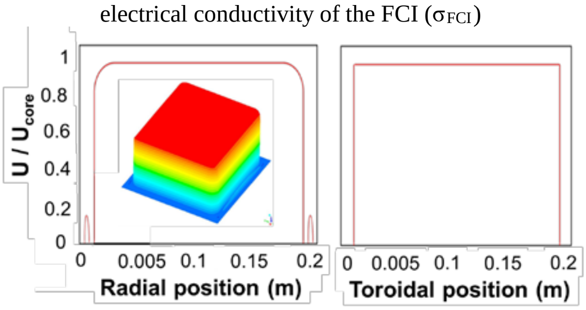

Fig. 3. Velocity profile in the cross-section of the FCI with respect to the radial and toroidal dimensions, considering an insulating FCI and a magnetic field of 4 T

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.

▪ 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 2. Main temperatures of the temperature field considering an insulating FCI of 10 W/(m·K)

ΔT_{FCI}	116 °C
$T_{max.\ bulk\ PbLi}$	678 °C
$T_{max\ .steel}$	536 °C
$T_{max.\ FCI}$	628 °C

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$T_{max. front gap}$	562 °C

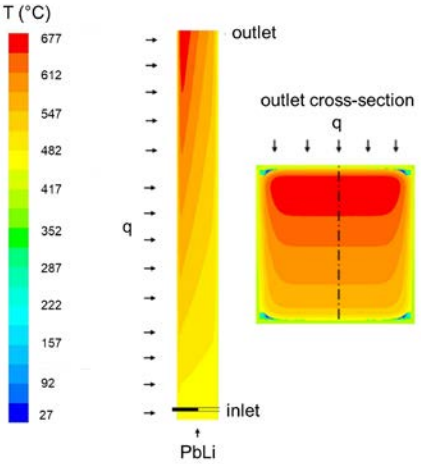

Fig. 4. Temperature map of the poloidal channel and in the outlet cross-section, considering an electrically insulating FCI of 10 W/(m·K)

The effect of the volumetric heating in the bulk PbLi can be observed; , being a considerable difference in the temperature of the steel wall closer to the heating source not noticed in these results. 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.

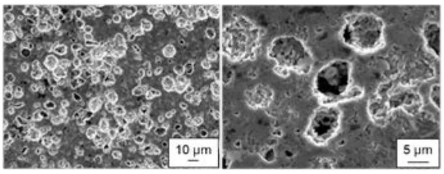

Fig. 5. Microstructure of a ~40% porous SiC material produced by uniaxial pressing

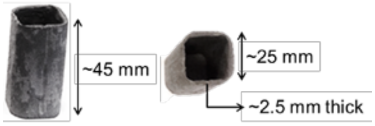

Fig. 6. Porous SiC hollow samples produced by gelcasting

The porous SiC materials were characterized in terms of their thermal and electrical conductivity, flexural strength and elastic modulus; the results can be found in [14] and in detail in [7]. In fig. 7, the thermal conductivity of the porous SiC at 700 °C is shown as a function of the porosity; an inverse exponential relationship was found between the two parameters. In fig. 8., the electrical conductivity of two of the materials produced, including a 200 µm dense SiC coating, is shown; the deposition of a dense layer by CVD was found not relevant in terms of the thermal conductivity of the material but this was not the case with the electrical conductivity, which increased after the CVD treatment [14]. The influence of subjecting the samples to a 1.8 MeV electron irradiation was also studied, observing a slight increase of the conductivity after irradiation.

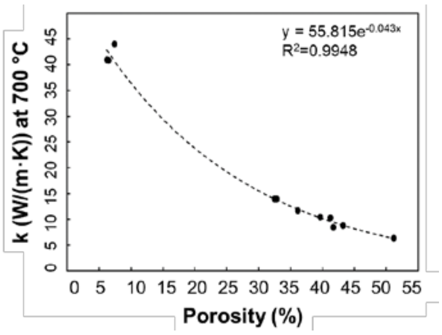

Fig. 7. Thermal conductivity of the SiC materials as a function of their porosity

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].

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

	~40% porous SiC
k_{porous} (W/(m·K))	~10 W/m·K
σ_{porous} (S/m)	< 1 S/m
E_{porous} (GPa)	118 GPa
Flexural strength (MPa)	80 ± 5 MPa

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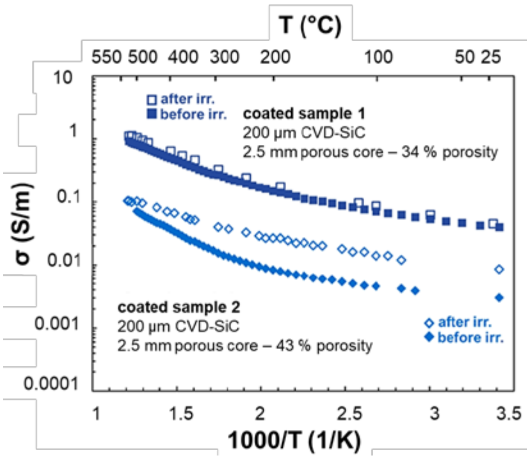

Fig. 8. Electrical conductivity of two SiC-based sandwich samples with different porosities in the core, as a function of the inverse of temperature, before and after the influence of electron irradiation

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 (as a power outage causing the solidification of the PbLi) provoked the breakup of 3 out of 4 of the samples tested, despite the good response of the coating observed after the test. Failures must be avoided in future experiments; the quality of the hollow SiC channels should be also improved to increase its mechanical strength. A picture of some of the samples after the corrosion experiments against flowing PbLi is shown in fig. 9.

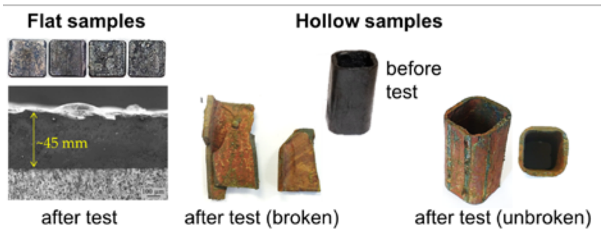

Fig. 9. Flat and hollow samples tested against flowing PbLi at 550 °C and 10 cm/s for 1000 h, coated with a 200 µm dense CVD-SiC layer

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

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7. References

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