INNOVATIVE DESIGN AND MATERIAL SOLUTIONS OF THERMAL CONTACT LAYERS FOR HIGH HEAT FLUX APPLICATIONS IN FUSION

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ABSTRACT

One of the most critical issues associated with the design and development of sacrificial plasma facing components that have to handle the high heat and particle fluxes in ITER is achieving the necessary contact conductance between the plasma protection material and the high-conductivity material in contact with the coolant.

This paper presents a novel bond idea which is proposed as one of the options for the sacrificial energy dump targets located at the bottom of the divertor legs and provides armour thermal and electrical contact with the cooled sub-structure while promoting remote, in-situ maintenance repair and an easy replaceability of the armour part without disturbing the cooling pipes or rewelding neutron irradiated materials. To provide a reliable and demountable adhesion the bond consists of a metal alloy, treated in the semi-solid region in such a way as to lead to a fine dispersion of a globular solid phase into a liquid matrix (rheocast process [1]). This thermal bond layer could be made working in the solid state during normal operation and could be brought reversibly in the semi-solid state during the armour replacement simply by heating it slightly above the solidus temperature.

The results of some preliminary thermal-mechanical analyses carried out to assess the heat transfer performance of these joints are reported in this paper together with some highlights on the key design, material, and remote maintenance issues which need to be rapidly addresses in the course of a R&D program.

I. INTRODUCTION/ BACKGROUND

Contrary to conventional target plate designs (see for example Ref. [2]), the present design of ITER divertor, relies upon extinguishing the plasma before it reaches the target plate by interaction with hydrogen neutrals or other seeded impurities along the length of the divertor channel and therefore redistributing the SOL power onto a much larger surface than conventional target plate design permits, while maintaining good control of impurities. The physics of the ITER divertor is fully elucidated in Ref. [3], while for the engineering, design and materials aspects involved in the development of the ITER divertor, the interested reader is referred to Ref. [4].

Plasma facing components in ITER will consist of a layer of sacrificial material facing the plasma (today's primary candidate is beryllium but other candidates are under considerations), and a high-conductivity actively cooled substrate material. Several duplex structure concepts combining armour materials mechanically attached or bonded to the heat sink have been proposed in the past. The most critical issue associated with making the proposed design concepts work from a power handling point of view, is achieving the necessary thermal conductance between the sacrificial protection and the coolant structure parts. Mechanical attachment schemes based, for example, on the use of solid compliant layers (e.g., metal fibre/ metal foam), held together only by mechanical pressure exhibit a thermal conductance which is too low for the high heat fluxes expected for components such as the divertor. Besides, providing a high contact pressure over most of the area will be a challenge even on initial installation and maintaining that high level over the life of the component, given the dimension and stress effects resulting from irradiation, will be very difficult. Bonding attachments, such as brazing, have a superior thermal conductance with respect to mechanical attachments. As a matter of fact, providing the high contact pressure required to ensure a high level of thermal conductance across the interface, over most of the area, will be a challenge even on initial installation and maintaining that high level over the life of the component, given the dimension and stress effects resulting from irradiation, will be very difficult. However, for brazed joints, most of the database available today is still inconclusive in terms of the integrity and of the expected lifetime of the interface in such designs for typical reactor conditions. In addition, bonding techniques, such as brazing, have the disadvantage of not allowing replacement of damaged tiles on the heat sink material, without replacing the heat sink itself. If in situ repair of the protection material (i.e., plasma-spraying) will not prove to be feasible or too time consuming for frequent repair intervention, or for other reasons a brazed design will not work, it is clear that other techniques must be used.

In this paper, we describe a novel joint idea which has been recently proposed for the sacrificial energy dump targets located at the bottom of the inner and outer divertor legs whose design constraints and operation requirements place critical demands on armour/heat sink joints, and for which in-situ replacement of the protective armour without cutting and rewelding the cooling pipes in a still high neutron flux region, is seen as a very important feature.

This bond consists of a binary or more complex alloy, treated in the semi-solid region in such a way as to lead to a fine dispersion of a globular solid phase into a liquid matrix (rheocast process). The alloy in this "mushy state" exhibits a time-dependent, shear rate-dependent viscosity, which is maintained reversibly when the material is solidified and heated again in the semi-solid state. A number of different thermal contact materials are being considered for this purpose. No contact pressure is required to provide the heat transfer conductance and a mechanical locking system has to guarantee positioning and avoid movements of the sacrificial part. The reversible thixotropic properties of the rheocast material should guarantee the stability of the layer in the semi-solid conditions during maintenance and repair and allow its in-situ reuse and a mechanical locking system has to guarantee positioning and avoid movements of the sacrificial part.

Definition of the main design requirements, description of the design concept features are reported here together with the results of some preliminary analysis performed to evaluate the required thermal and electrical performance of the joints, for the anticipated ranges of operation conditions. Remote maintenance issues concerning installation and replacements of the damaged or worn out armour are also discussed in this paper, while considerations regarding bond material selection and testing which be addresses in the course of a development program are reported in ref. [5,6] and are only outlined here.

II NOVEL THERMAL CONTACT JOINTS

A. Concept description

The energy dump targets located at the bottom of the divertor channel, due to the anticipated harsh conditions (the dump targets are designed to receive a steady state power load of < 10% of the energy conducted into the SOL assuming that 90% is radiated or lost by neutral collisions and to absorb heat pulses originating from ELM's and disruptions) will very likely require frequent replacements. The protection material should be sufficiently thick in order to maximise the lifetime of the plate which is anticipated limited by erosion due to disruptions, while allowing for a steady-heat load of up to 5 MW/m^2.

A schematic representation of the design concept which will be discussed in this paper is shown in Fig. 1. It consists of a Be protection (in brush or castellated form) brazed onto Cu plates with a meander structure on the opposite surface to increase the surface area and thermal transfer efficiency. The meander structure is then thermally bonded with a rheocast alloy onto a water cooled Cu meander structure. An interpenetrating structure is deemed preferable since it resists shearing at the interface and prevent lateral displacements. This could help minimise the formation of interfacial voids in the compliant material, if large deformations, such as bowing, occurs under operation. We are analysing for the time being a solution with a small number of sparsely distributed fins, i.e., only one fin on each site of a coolant passage. This minimises the distance between the coolant and the armour. However, definition of an optimum geometry, attachment/locking scheme as well as replacement method and testing of the thermal bond are R&D tasks.

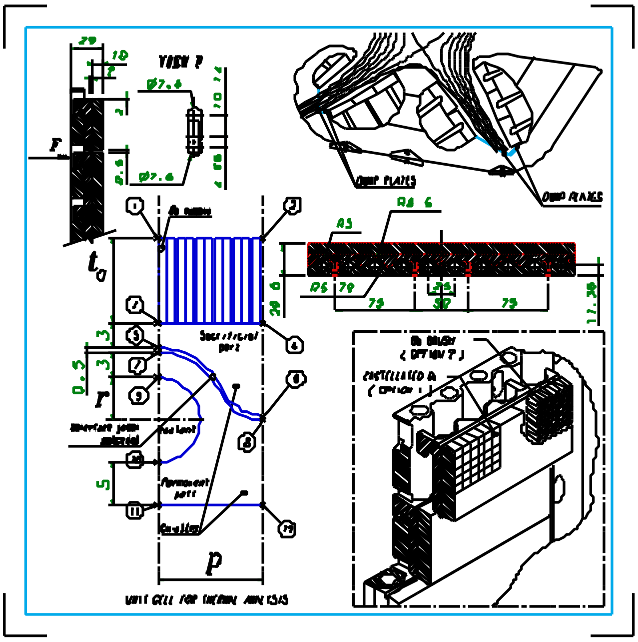

Figure 1: Dump Plate Concept

B. Design Requirements and Features

The first step in developing a compliant armour-heat sink interface joint for ITER is to identify and define design requirements. This is essential to guide the R&D

activity and assure that the correct issues are being addressed.

Table 1 summarise some of the requirements for thermal contact layers while Table 2 describes some of the design features of this inovative joint.

Table 1: Summary of requirements for thermal contact compliant layers for PFC's.

- provide sufficient thermal conductance to cool the protection material during normal operation and off-normal events;
- provide sufficient mechanical strength to maintain alignment during normal operation, and off-normal events;
- provide sufficient electrical conductivity to pass halo currents;
- provide sufficient thickness to compensate for fabrication and assembly tolerances;
- provide compliancy to accommodate differential thermal expansion for expected temperature excursions;
- provide adequate lifetime in anticipated ITER radiation environments;
- consist of low-vapour pressure and outgassing materials;
- provide for easy disassembly during maintenance operations and for remote, in-situ replacement.

Table 2: Key design/ material features of innovative joints described in this paper.

HIGH HEAT FLUX CAPABILITY:

- actively cooled to limit the temperature at the beryllium surface below 800˚C during normal and transient operation;

EASILY REMOVABLE ARMOURS, LEAVING THE COOLING SYSTEM IN PLACE:

- the bond between the sacrificial armour and the permanent heat sink is achieved via solder/braze alloy in the rheocast condition.
- the interface joint material is in solid form under normal operation and could be brought reversibly to semi-solid state during replacement of the armour simply by heating it slightly above the solidus temperature.
- allows (in principle) easy replacement of the protection part without disturbing the cooling pipes or rewelding neutron irradiated materials

COMPONENT INTEGRATION:

- no contact pressure is required to provide the required heat transfer conductance.
- a mechanical locking system provides the attachment/positioning of the sacrificial pert to the permanent one

C. Candidate Joint Materials

A number of different options are being investigated for this purpose and presently the most attractive solutions consists of using a binary or more complex alloy, treated in the semi-solid region in such a way to lead to a fine dispersion of a globular solid phase into a liquid matrix (rheocast process). The rheocast processing technology, consists in vigorously stirring an alloy featuring a large solidification temperature range at a temperature corresponding to an approximately equal proportion of the solid and liquid phases. The process leads to a fine dispersion of a globular solid phase into a liquid matrix [5]. The alloy in the “mushy state” has at least two features which make it potentially interesting for its use as a compliant layer. First of all the semi-solid slurry is thixotropic. Thixotropy results when a material exhibits a time-dependent, shear-rate dependent viscosity. When the material is sheared it thins; when undisturbed, it thickens again. Secondly, cooling below the liquidus temperature freezes this microstructure, but heating again above the solidus restores the thixotropic properties. The metal structure and its rheological properties are retained after solidification and partial re-melting.

Ref. [5,6] reviews the work performed to date on this subject, including identification of interface material candidates and preliminary wettability tests on some attractive solder materials (90%In, 10%Ag - 95%Bi, 5%Sn - 90% Sn, 10%Ag - 97%Sn - 3%Cu, 99%Sn, 1%Ge). These alloys are attractive because they have a low vapour pressure, have a relatively wide separation between solidus and liquidus temperature and have a liquidus temperature below 350˚C which eases in-situ refurbishment. They should function in the solid state during normal operating conditions for the water-cooled divertor currently being considered for ITER. However, the proposed 300°C bake-out temperature suggests that the list be expanded to include higher temperature alloys.

III.REMOTE MAINTENANCE CONSIDERATIONS

The major advantage of this novel design approach over more traditional approaches is the ability to remove and replace the plasma facing surface without breaking coolant connections or removing an entire divertor segment. The steps required to replace a section of the surface, i.e. assembly, include: (1) bringing the rheocast material to its semi-solid state by raising the temperature of this layer to a value between its solidus and liquidus temperature, (2) releasing the mechanical locking connections which are used to properly position the assembly and resist mechanical loads, (3) removing the old assembly and replacing it with a new one, (4) allowing the rheocast material to wet the surface of the new assembly, and (5) cooling the rheocast material below its solidus temperature.

A straightforward method for achieving the desired temperature of the rheocast material during removal and replacement is through control of the temperature of a fluid that is forced through the divertor coolant passages. The high temperature fluid might be a gas such as superheated steam, helium or nitrogen. Selection of the appropriate thermal control medium will depend on the solidus and liquidus temperatures of the selected rheocast material. The use of a more localised heating and cooling approach, that would expose only the sections of the plasma facing surface needing replacement to elevated temperatures, would be desirable. However, since this is not considered to be an essential requirement, the hot fluid approach is the reference concept because of its simplicity.

The procedures called for in Steps 2 and 3 above, require the release of mechanical locking mechanisms, such as those shown in Fig. 1, and removal of the damaged assembly. These operations will require the use of special purpose remote handling tools. Since these special purpose tools depend on the details of the design which are still under development, these tools are not yet defined. To illustrate the removal procedure, the sequence of operations required for the reference design shown in Fig. 1 is described below.

Engagement fittings or fixtures will be incorporated in the design shown in Fig. 1 to allow remote handling tools to grab and move the assembly. After engaging the assembly fittings, the assembly is moved in a path parallel to the coolant passages until the latch mechanism is unlocked and the assembly is no longer trapped by its neighbour. The assembly can then be removed with a motion that is perpendicular to the initial one. The motions required for installation will be essentially the reverse of those for removal. Elimination of the motion parallel to the coolant passages is desirable to avoid the possibility of having to remove several assemblies to gain access to the damaged one. However, the simplicity and robust structural characteristics of the reference concept are judged to outweigh the advantages of attachment schemes which bolts or other fasteners requiring head-on engagement of locking mechanisms. It should be noted that the remote handling tools used in the installation may be required to handle, and perhaps actively maintain, the new assembly at a temperature near that of the semi-solid rheocast material so that solidification does not occur before the rheocast material can wet the new surface.

Consideration of each of these removal and replacement steps must be part of the ongoing divertor and remote handling system design and R&D activities. Since replacement of assemblies is expected to be a relatively frequent operation, final verification testing to demonstrate this procedure with prototypical divertor target surfaces and remote handling equipment is essential to the remote handling operations.

IV. PERFORMANCE PREDICTIONS

A. Heat transfer/ Thermal-Mechanical Analyses

This analysis was performed to assess the heat flux capability of the proposed joint as well as the thermal performance of imperfect joints and evaluate how much detachment can be allowed during the operation..

The unit cell assumed for the thermal analysis is shown in Fig. 1. The dimensions are shown on the figure. Finite element steady-state thermal calculations were performed using the ANSYS code [7]. The thermal conductivity in the normal direction through the beryllium armour was assumed to be 80% of the conductivity for Be with a density equal to its theoretical density and 20% in the parallel direction. The heat transfer coefficient between Cu alloy and water (T_c = 100˚C) was set equal to 50 kW/m^{2}K (which corresponds to about a velocity of 10 m/s in a 10 mm smooth tube). The resulting pressure drop per meter length is of 0.1 MPa and the calculated coolant temperature rise per meter at 3MW/m2, for a 25 mm pitch was of about 25 ˚C. The results of the thermal analysis performed varying the value of the thermal conductivity of the bond material for several values of the surface heat flux assuming perfect interface contact (i.e., no debonding) are summarised in Table 3

Table 3: effect of thermal conductivity of the bond material on heat transfer performance of the plate for different values of surface heat flux assuming no debonding)(a) 5 mm Be armour ; (b) 10 mm Be armour.)

		Surface Heat Flux								
		1 MW/ m^2			**3 MW/ m^2**			**5 MW/ m^2**		
Bond Therm. Conduc. (W/m-k)		T_{Be} max. (˚C)	T_{Cu} max. (˚C)	T_{Tb} max. (˚C)	T_{Be} max. (˚C)	T_{Cu} max. (˚C)	T_{Tb} max. (˚C)	T_{Be} max. (˚C)	T_{Cu} max. (˚C)	T_{Tb} max. (˚C)
10	a	241	195	185	557	378	348	910	567	514
10	b	295	197	187	764	380	350	1261	570	516
50	a	206	162	150	443	280	246	720	402	343
50	b	255	163	151	635	281	247	1071	404	344
100	a	201	157	145	429	268	232	695	382	320
100	b	251	159	147	619	269	233	1045	383	321

Table 4 shows the temperature along the joint interface assuming an impinging heat flux of 3 MW/m^2 for the case of full contact and includes the effect of progressive detachment of the interface bond starting from the point of the interface nearest to the plasma surface (Cases A) and starting from the point the interface farthest from the plasma (Cases B). No heat transfer across the interface due to radiation was assumed in the case of detachment. From these initial results, it appears that adequate heat transfer across the interface joint can be maintained even when substantial debonding takes place along the interface, provided initial wetting is good.

In regions of high heat flux, the ability to maintain acceptable temperatures and stresses and deformations in the joint is a major concern. Stress in the joint due to CTE mismatch, thermal stress related cracking, contact pressure requirements, cycling effects, response to disruption loads are just examples of the problems which one should investigate. In particular the allowable deformation of the joint prior to failure, under service conditions is very important. Ref. [5] reports on the compliance characteristics of the joint and evaluate the relative deformation (e.g., thinning or expansion) of the thermal bond material induced by the temperature. Although those results are still preliminary, it seems that the deformations could be accommodated at the most with some minor design modifications of the finned interface. Further theoretical and experimental analyses are required to better elucidate this aspect and ultimately evaluate the allowable deformation of the joint prior to failure

B. Electric Effects and Electromagnetic Loads

Given the limited information on electrical properties of compliant layers and incomplete characterisation of the currents (halo and eddy) and the associated electrromagnetic forces which will arise during abnormal events (i.e., disruptions, VDE's) it is very difficult at this stage to provide some quantitative conclusions on this subject. The current loads are estimated to be up (halos) and This will result in ...TO BE COMPLETED BY STEFANO CHIOCCHIO

Other crucial aspects which need to be investigated are the occurrence of arcing effects and the consequent blow-off of the joint material and the micro cracking and debonding induced contact resistance at the interface under thermal cycling and neutron damage

Table 4: effect of debonding on temperature (˚C) across the plate for an impinging heat flux of 3 MW/m^2

FRACTION DEBONDING	ARMOUR T_{Be}		HEAT SINK T_{Cu}		THERMAL BOND T_{TB}	
	max.	min.	max.	min.	max.	min.
full contact	635	278	281	126	247	166
CASE A						
• 1/6	673	297	317	127	275	171
• 1/3	754	338	385	131	298	182
• 1/2	862	416	477	137	322	199
• 2/3	1003	536	604	127	356	209
• 5/6	1215	742	814	122	484	279
CASE B						
• 1/6	645	283	289	123	252	159
• 1/3	671	298	310	119	265	169
• 1/2	721	324	352	117	288	196
• 2/3	827	381	445	115	355	232
• 5/6	1058	538	660	113	500	291

CASE A Progressive detachment of the interface bond starting from the point nearest to the plasma facing surface;
CASE B Progressive detachment of the interface bond starting from the point farthest from the plasma facing surface;

C. Lifetime evaluation

Although not directly affecting the bond itself, erosion of the sacrificial armour due to physical sputtering and ELM's and disruptions, rather than mechanical failure due to cracking is anticipated to set the durability of the joint. In circumstances when heat pulses due to disruptions or Elm's burn through the gas target and arrive at the energy dump target, evaporation and possibly melting of the surface of these targets will be unavoidable.

The exact amount of material eroded from both ablation and melting is critically important to evaluate the component lifetime. It is difficult at this stage to make predictions on the lifetime of these components due to the uncertainties of the operation conditions (frequency of occurrence of disruptions, energy density, duration, plasma-particle kinetic energy during disruptions, etc.), and to the discrepancies of most of the experimental database available to evaluate the effect of phenomena such as vapour shielding and plasma shielding which could substantially mitigate the resulting damage. As an upper limit the amount of material evaporated during a disruption for different energy densities deposited in very short times without including vapour or plasma shielding effects ranges between 200 and 1000 µm per event assuming energies deposited between 10 MJ/m^2 to 100 MJ/m^2. The effect of shielding is presently estimated to be within a factor of 10 to 100 and therefore could significantly extend the lifetime of the component. It is then clear that in order to increase the lifetime a requirement would be to add armour thickness that can be eroded during plasma operation, while keeping the maximum Beryllium temperature below 800-900˚C to minimise losses due to material sublimation. The use of a different plasma protection material (e.g., W rather than Be) could be beneficial in this respect as its practically negligible sublimation up to about 2000˚C).

V. DEVELOPMENTAL ISSUES AND R&D NEEDS

Several aspects are involved with the design and development of thermal contact bonds. They include material issues (i.e., wetting, chemical, vacuum and plasma compatibility, in-situ reuse of the compliant layer, shrinkage during solidification, stability of the rheocast structure under repeated partial melting cycles), fabrication issues, heat-transfer issues (i.e., optimum configuration, contact area, compliance with respect to the relative displacement of the two adjacent surfaces, micro cracking and debonding effects), mechanical issues (stress due to thermal expansion mismatch, bond integrity, thermal stress related cracking, contact pressure requirements, cycling effects, response to disruption loads), tritium effects like diffusion and permeation, radiation damage effects (microstructural changes, change of the wettability characteristics, embrittlement, transmutation products, swelling), and the remote maintenance issues (installation, replacement).

These issues were used to develop an R&D plan which will be implemented in order to screen material options, evolve the design concepts, and demonstrate their feasibility for use in ITER. A phased work plan for thermal bond development is described in Ref. [5,6].

VI.SUMMARY

This paper describes an innovative interface joint between the sacrificial armour and the actively cooled permanent heat sink which consists of a thermal bond layer of solder or braze alloy in the rheocast condition. A design of the dump plate for the ITER divertor based on this concept appears possible which can take a heat flux of at least 3 MW/m^2 and depending on the material and the thickness of the armour much higher heat loads.

Initial thermal-mechanical estimates suggest that a relatively large amount of debonding can be accommodated.

The tile must not be only adequately designed from a heat transfer and particle flux standpoint but also must be easily replaceable using remotely operated equipment.

Several critical design and remote maintenance issues have been identified and discussed in this paper.

Further analysis and the findings of the ongoing R&D program will be needed before any final decisions can be made on the acceptability or relative advantages of these options.

ACKNOWLEDGMENTS

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