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Design, materials and R&D issues of innovative thermal contact joints for high heat flux applications

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Abstract

Plasma facing components in fusion machines are designed with a layer of sacrificial armour material facing the plasma and a high-conductivity material in contact with the coolant. One of the most critical issues associated with making the proposed design concept work, from a power handling point of view, is achieving the necessary contact conductance between the armour and the heat sink.

This paper presents a novel idea for the interface joint between the sacrificial armour and the actively cooled permanent heat sink. It consists of a thermal bond layer 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. The function of the thermal bond layer is to facilitate heat transfer between the replaceable armour and the permanent heat sink without building up excessive thermal stresses, as in conventional brazed joints, and allow an easy replacement whenever needed without disturbing the coolant system. No contact pressure is required in this case to provide the desired heat transfer conductance, and the reversible thixotropic properties of the rheocast material should guarantee the stability of the layer in the semi-solid conditions.

Key design, material and testing issues are identified and discussed in this paper with emphasis on specific needs for future research and development work. Examples of suitable material options which are being considered are reported together with some initial heat transfer analysis results.

1. Introduction

One of the most challenging issues in designing plasma facing components for the next generation of tokamaks is the development of reliable joints between the sacrificial plasma facing armour material and a high-conductivity actively cooled heat sink material. Approaches which have received widespread attention in the past include mechanical attachment, held together only by mechanical pressure, and bonded attach-

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ments, such as brazing. A bolted joint with solid-to-solid contact between the armour and substrate is the simplest approach, but also suffers several critical concerns. The interface conductance in this case depends strongly on the pressure exerted by the attachment. Thermal stresses can deform the interface, causing non-uniformities and a net reduction in contact conductance. Thermal and radiation creep can relax the contact pressure, and reduce the contact conductance. Depending on the materials and temperature at the joint, permanent diffusion bonding could occur between the armour and substrate, making detachment difficult or impossible.

Another approach which has received widespread attention is the use of metallic or graphite "felt" materials. These materials also require some amount of compression in order to achieve adequate and reliable thermal conductance. They provide a greater degree of "compliance" to accommodate differential thermal expansion between the armour and substrate. In order to provide better thermal conductance with reduced contact pressure, a combination of felt plus braze has been proposed. The braze can be applied to the surface only, or impregnated throughout the entire bulk felt. Non-bonded felt/braze combinations can offer superior contact conductance and mechanical compliance as compared with solid metal-to-metal contact, but they still require some amount of (albeit much less) contact pressure to maintain the thermal performance. The advantage of impregnated felt over a simple braze joint is that the felt can provide a solid framework to prevent liquid from leaving the bond site during installation and replacement.

Past testing has shown that purely mechanical attachment, including insertion of compliant felt or metal foam, results in a thermal conductance which is too low for the high heat fluxes expected for components such as the divertor. Furthermore, providing a high contact pressure over most of the area would be a challenge even on initial installation; maintaining that high level over the life of the component, given the dimension and stress effects resulting from irradiation, would be very difficult.

The only method which provides acceptable thermal performance without any contact pressure is a fully-bonded joint. Brazed attachments have been proposed for plasma facing components in many earlier studies because of their superior thermal conductance as compared with mechanical attachment schemes. However, the central issue then becomes the interface stresses in the bond region caused by the mismatch in thermal expansion between the plasma facing material and the heat sink material. These large stresses in the interface region make it challenging to reliably fabricate and maintain adequate bonding between the two materials using reasonably-sized pieces, i.e. larger than a few square centimetres. In addition, the refurbishment of brazed armour layers involves cutting and re-welding coolant lines in a radiation environment which is time-consuming and difficult. Advanced bonding concepts have been proposed wherein the interface region is engineered to provide a gradient in thermal expansion so that the stress discontinuity is relaxed. A particular concern with beryllium armour is the formation of brittle intermetallic compounds at the braze interface. Only four metals resist formation of stable beryllides below 760 °C: aluminium, silicon, silver and germanium. The joint design is further complicated by the low ductility of beryllium. For brazed joints, the current database is still inconclusive in terms of the integrity and the expected lifetime of the interface under typical reactor conditions.

Given these problems, some exploratory assessments and trade-studies are under way to evaluate new interface joint design ideas and materials alternatives, as a part of the International Thermonuclear Experimental Reactor (ITER) research and development work. A number of different options are being investigated for this purpose and one of the most attractive consists of using a layer 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 (thixotropy), which is maintained reversibly even when the material is solidified and then heated again in the semi-solid state. No contact pressure is required in this case to provide the desired heat transfer conductance, and 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 re-use.

This paper reviews the work performed to date on this subject, including identification of interface material candidates, consideration of optimum interface configuration, design and material issues of concern, operational performance, and anticipated repair methods. Specific needs for future research and development are discussed in light of the design evolution anticipated in ITER.

2. Innovative materials/design joints

2.1. Concept description

As discussed in Ref. [1] an interpenetrating structure is deemed preferable since it resists shearing at the

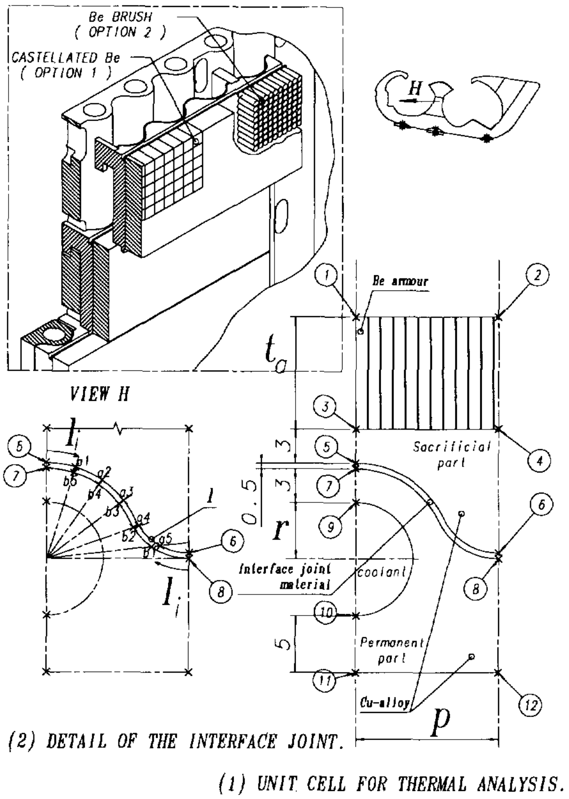

Fig. 1. Schematic of the concept and detail of the interface joint.

interface and prevents lateral displacements. This could help minimise the formation of interfacial voids in the compliant material if large deformations, such as bowing, occur under operation. As shown in Fig. 1, 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. Results of some preliminary analysis aimed at optimising the shape of the thermal bond interface from a heat transfer standpoint are reported below.

2.2. Requirements/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 ensure that the correct issues are being addressed.

Thermal bond layers for PFCs must:

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

The list above is rather qualitative but more precise and quantitative requirements are expected to be formulated soon. Table 1 summarises some of the underlying features of the proposed interface joint concept.

2.3. Materials selection

The rheocast processing technology, identified nearly 20 years ago by Professor M. Flemings and co-workers at MIT [2], consists of 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. The alloy in the "mushy state" has at least two features which make it potentially interesting for use as a thermal bond. 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 solidus 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.

A rheocast thermal bond layer could be made to work in the solid state during normal operation and could be brought into the semi-solid state during ar-

Table 1
Key design and 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 armors, leaving the cooling system in place
- The bond between the sacrificial armor 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 armor, simply by heating it slightly above the solidus temperature
- Allows (in principle) easy replacement of the protection part without disturbing the cooling pipes or re-welding neutron-irradiated materials

Component integration
- No contact pressure is required to provide the required heat transfer conductance
- A mechanical locking system provides the attachment and positioning of the sacrificial part to the permanent part.

mour replacement simply by heating it slightly above the solidus temperature.

Some binary phase diagrams were inspected to identify suitable material combination candidates.

All types of alloy system, solid solution, eutectic, peritectic, monotectic, can in principle be treated to develop a rheocast structure, although the examples reported in the literature are limited to solid solutions or eutectic systems. Considering the temperature and composition dependence of the liquid volume fraction V_l, the different systems behave differently, as shown in Fig. 2. In solid solutions (Fig. 2(a)), V_l varies from 0% to 100% as the temperature varies from T_{solidus} to T_{liquidus}, irrespective of composition. Moreover, the solidification temperature range $T_l - T_s$ is in general limited and is weakly dependent on composition.

In eutectic and peritectic systems, represented in Figs. 2(b) and 2(c) respectively, the composition determines the value of V_l at the temperature T_s. As the temperature rises, V_l increases steadily up to 100% at T_l. The solidification range depends strongly on composition.

In monotectic systems the value of V_l depends only on the composition, since it remains practically constant in the temperature range of co-existence of liquid and solid phases, which is very extensive and independent on composition in a wide concentration range.

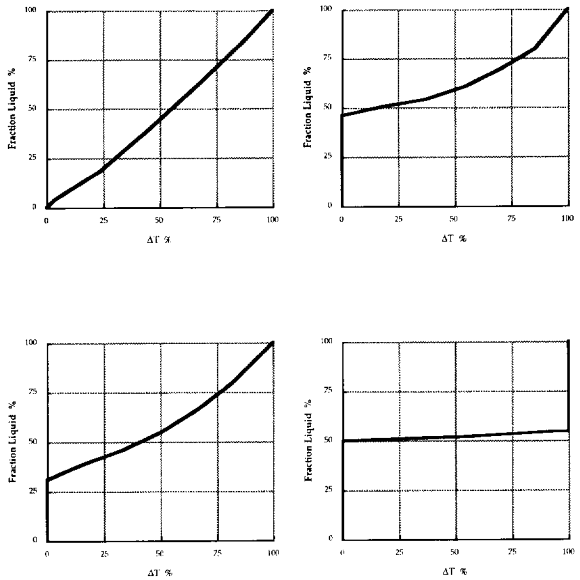

Fig. 2. Fraction of liquid V_l vs. variation of temperature from T_{solidus} to T_{liquidus} (for $\Delta T = 0\%$, $T = T_{\text{solidus}}$; for $\Delta T = 100\%$, $T = T_{\text{liquidus}}$) for (a) solid solution, (b) eutectic, (c) peritectic, and (d) monotectic.

Since the thixotropic properties strongly depend on V_l, the monotectic systems seem to have the most interesting features from the maintenance point of view. As a matter of fact, whereas for solid solutions and, to a lesser extent, for eutectic and peritectic systems, the temperature range of stability of the rheocast structure is limited and the thixotropic properties are strongly dependent on temperature, for monotectic system the opposite is true. Another advantage of the latter system is that the two phases are in general constituted by almost ductile pure elements and not by brittle intermetallic phases.

Several potential material options exist with different compositions and properties. In the temperature range 200–400 °C, In, Sn, and Bi alloys (usually called "solders") are attractive. Above 400 °C, Cu, Ag, and Al alloys (usually called "brazes") must be considered. Material systems to be coupled to Be include vanadium alloy, stainless steel, and Cu–Cr–Zr. Carbon and Be fibre composites are also to be considered as armour options. At this time, the primary coolant option for ITER is water, so that the peak temperature of the joint is of the order of 300 °C under normal operation. Given this fact, and considering the other material issues and properties, the primary candidate compliant materials (and their solidus and liquidus temperatures) we have

Table 2
Candidate compliant layer materials

Solder type	Solidus temperature (°C)	Liquidus temperature (°C)
90% In, 10% Ag	141	237
95% Bi, 5% Sn	134	251
90% Sn, 10% Ag	221	295
97% Sn, 3% Cu	227	300
99% Sn, 1% Ge	232	345
90% Pb, 10% Sn[a]	275	302
95% Pb, 5% Ag[a]	305	364
90% Pb, 10% Ag[a]	305	450
55% Ge, 45% Al[a]	424	424
86% Al, 10% Si, 4% Cu[a]	521	585

[a] These alloys are of interest but have not been evaluated.

considered for future testing are summarized in Table 2. We have done some wetting studies with the top five lower-temperature alloys in this table. The results of these studies are presented in Section 4.

3. Preliminary performance predictions

3.1. Interface heat transfer analysis

An analysis was performed to assess the heat flux capability of the proposed concept and the influence of debonding effects taking place at the joint interface on temperature distributions. 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 [3]. 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 5×10^4 W m^{-2} K^{-1} (which corresponds to a velocity of about 10 m s^{-1} in a 10 mm smooth tube). A value of 50 W m^{-1} K^{-1} was assumed for the 0.5 mm compliant material layer. Table 3 shows the temperature at different characteristic points 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). 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. Additional thermal analysis results are presented and discussed in Ref. [4].

3.2. Thermal–mechanical analysis

A preliminary 2-D thermal–mechanical analysis was also performed using the temperature input available from the analysis discussed in Section 3.1 and the aforementioned code ANSYS [3]. As the absolute bond strength is not as important as the amount of deformation prior to failure, the aim of this analysis was limited to establishing the compliance characteristics of the joint and evaluating the relative deformation (e.g. thinning or expansion) of the thermal bond material induced by the temperature distributions resulting under normal operation. The evaluation of the absolute bond strength, including effects of void content over varying thickness, represents the subject of a more detailed analysis which will be carried out in the future. Owing to the lack of more precise mechanical property data for the thermal bond materials, this analysis was performed assuming a very soft compliant material (e.g. very low Young's modulus of about 1 GPa, CTE of about 18.5×10^{-6} K^{-1} and Poisson modulus of about 0.36). The values of the mechanical properties used for Be and CuCrZr alloy were taken from the literature. The deformation of the gap in the normal direction is shown for the case of full interface contact in Fig. 3, together with the variation of the gap thickness along the interface joints, assuming plane stress conditions, and imposing a free boundary expansion at the right side of the sacrificial plate, while constraining the lower permanent part to a purely horizontal expansion (no bending). Under these conditions, which were deemed to be conservative, the results of the analysis showed that the expansion of the thermal contact material (first part of the joint near the plasma facing surface) or its thinning (part of the joint away from the plasma facing surface) are not exceeding 20 μm. Although further theoretical and experimental analyses are required to determine ultimately the allowable deformation of the joint prior to failure, from these preliminary results it seems that the deformations could be accommodated at the most with some minor design modifications of the finned interface.

4. Initial test results and test plan

Five binary solder alloys were identified for preliminary evaluation as thermal bond materials. The alloys

Table 3
Effect of debonding on temperature distribution across the plate for an impinging heat flux of 3 MW m^{-2}

Fraction of debonding	Armor T_{Be} (°C)		Heat sink T_{Cu} (°C)		Thermal bond T_{TB} (°C)	
	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 furthest from the plasma facing surfaces.

Main working assumptions as follows: (1) thermal conductivity in the normal direction through the beryllium armor was assumed to be 80% of the conductivity for beryllium with a density equal to its theoretical density and 20% in parallel direction; (2) thermal conductivity of the thermal bond material is 50 W m^{-1} k^{-1}; (3) no heat transfer across the interface resulting from radiation was assumed in the case of detachment.

are listed in the top section of Table 2. These alloys are attractive because they (1) have a low vapour pressure, (2) have a relatively wide separation between solidus and liquidus temperature and (3) 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 such as those indicated in the lower section of Table 2. Candidate alloys from this list will be included in future evaluation studies.

The preliminary work reported here considers only wetting studies on copper substrates. The wetting figure of merit is the angle formed at the solder/substrate interface. Wetting angles are determined from the diameter and height of the reflowed solder assuming a spherical cap geometry. Some samples were later cross-sectioned to compare the measured wetting angle with that resulting from the spherical cap model. There is generally good agreement between the two values. Wetting angles are being evaluated as a function of solder type, reflow environment and surface preparation technique for both the copper and solder. The solders with the best wetting characteristics will be subjected to further study, including solder diffusion into the copper substrate after ageing at expected operating temperatures (around 300 °C), and interface void content investigations as a function of thermal cycling.

Initial results of the wetting studies are presented in Table 4. This table shows that wetting is generally good for all materials except the bismuth-based solder. The Bi/Sn sample had an obviously high wetting angle with flux and appeared to form a ball on the surface. It was therefore eliminated for further testing. Aside from this result, Table 4 shows no clear discriminators between the solder materials from a wetting perspective. With proper surface preparation, good wetting is achieved, even without flux, for all of the remaining solders. This is encouraging because it indicates that under controlled conditions a good initial bond can be achieved without introducing flux into the vacuum environment.

In addition to the wetting, ageing and thermal cycling studies on simple coupon specimens, mock-ups of divertor dump plates joined by a thermal bond have been designed and fabricated for electron beam, high-heat-flux testing at the Plasma Materials Test Facility (PMTF) at Sandia National Laboratory. The PMTF

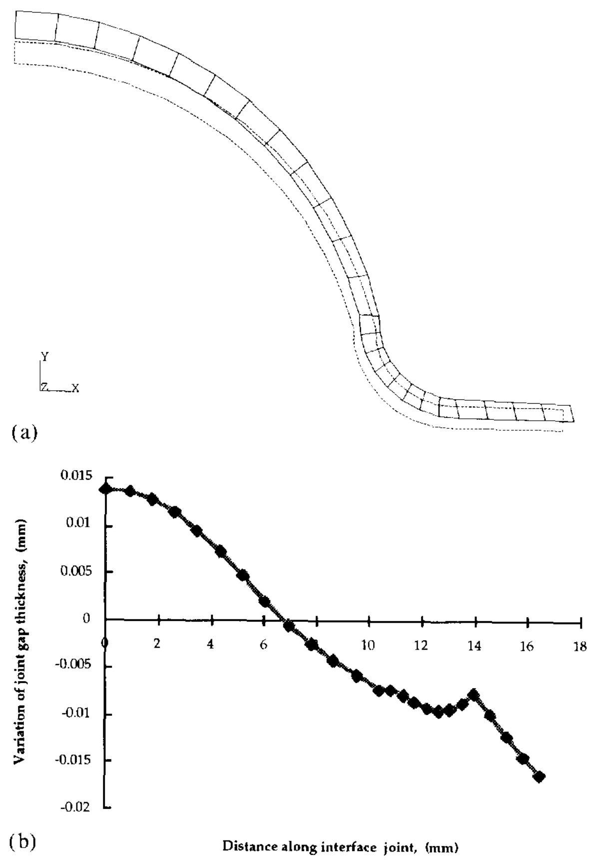

Fig. 3. (a) Deformation of the joint; (b) variation of the joint thickness (thinning (<0) or expansion (>0)) along the interface starting from the point nearest the plasma facing surface.

mock-ups consist of four 10 × 10 cm^2, finned copper plate sandwiches, each with a 0.2 mm thick solder joint. All mock-up parts have been fabricated. The mock-ups will be pre-wetted with candidate compliant materials on both upper and lower plates. A solder pre-form will then be inserted between the two plates and eight thermocouples installed. The assembly will finally be fired to 400 °C in a braze furnace with a hydrogen background. Based on the initial wetting results, In90/Ag10 solder will be used for mock-up fabrication. The HHF tests will measure changes in thermal conductivity during the phase transformation between solid and liquid and investigate the effects of thermal cycling on performance including possible void formation and de-wetting. The effects of thermal stress on thermal bond performance will also be investigated. The mechanical integrity of the test specimens and the robustness of the thermal bonds will be evaluated under various heat fluxes.

5. Key issues and research and development needs

A summary of key performance and R&D issues for thermal contact thermal bonds for PFCs is reported in Table 5. 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 shown in Fig. 4 [5]. The plan is structured to satisfy the development requirements in a cost-effective manner. It is broken into three phases of screening, testing and

Table 4
Summary of copper wetting studies with candidate solder alloys

Solder preparation	Copper preparation	Solder type	Process environment	Process max. temp. (°C)	Solder liquidus temp. (°C)	Solder solidus temp. (°C)	Measured angle (deg)	Calculated angle (deg)
Abrade	50/50 Nitric etch	In90–Ag10	Vacuum	398	237	141	10–12	8.1
Abrade	HCl + nitric	Sn90–Ag10	Vacuum	417	295	221		7.5
Abrade	HCl + nitric	Sn99–Ge1	Vacuum	467	345	232		7.1
Abrade	50/50 Nitric etch	Sn97–Cu3	Vacuum	450	300	227	9	9.3
Abrade	HCl + nitric	Sn97–Cu3	Vacuum	425	300	227		11.5
Abrade	50/50 Nitric etch	In90–Ag10	Flux/argon	271	237	141	5–7	5.9
Abrade	50/50 Nitric etch	Sn90–Ag10	Flux/argon	406	295	221	5–7	8.0
Abrade	50/50 Nitric etch	Sn99–Ge1	Flux/argon	456	345	232		12.1
Abrade	HCl + nitric	Sn97–Cu3	Flux/argon	420	300	227		6.3
Abrade	HCl + nitric	Sn97–Cu3	Flux/argon	520	300	227		5.7
Abrade	HCl + nitric	Bi95–Sn5	Flux/argon	365	251	134		Non-sphere

Table 5
Key performance and R&D issues for PFC interface thermal contact layers

- Materials issues
  - Wetting
  - Chemical compatibility
    - interalloying
    - oxidation effects and corrosion
    - protective coating of adjacent materials might be required
    - compatibility with air, water and steam
  - Vacuum compatibility
    - outgassing and surface area
    - trap volume (virtual leaks)
    - vapor pressure
  - Plasma compatibility
    - atomic number
    - vapor pressure
  - In situ reuse of the compliant layer
    - surface cleaning
    - preparation
    - replacement technique
    - welding of the material to the permanent heat sink substrate will hamper its removal during component replacement. (see remote maintenance below)
  - Shrinkage during solidification (cracking and debonding)
- Fabrication issues
  - Choice among solid solution, eutectic, peritectic or monotectic systems
  - Optimization of the rheocast treatment
- Heat transfer issues
  - Optimum configuration
    - gap limits, degree of compliance, etc.
  - Thermal conductivity
    - if the wetting of the solder or braze to the substrate is good, the interface resistance should be relatively small, with the entire joint resistance, calculated from the resistance of the bulk alone
  - Contact area
  - Compliance with respect to the relative displacement of the two adjacent surfaces
  - Microcracking or debonding-induced contact resistance at the interface under thermal cycling and irradiation damage
- Electrical properties
  - Layer resistance
  - Arcing and its effects (such as blowing off of the material)
- Thermal effects
  - Stability of the rheocast structure under repeated partial melting cycles
  - Microstructural stability under extended thermal treatment near the solid line

Table 5 (continued)

- Mechanical effects
  - Stress resulting from thermal expansion mismatch
  - Bond integrity and thermal stress-related cracking
  - Contact pressure requirements
  - Cyclic effects
  - Response to disruption loads
- Tritium effects
  - Tritium diffusion and trapping
  - Hydride formation
- Radiation damage effects
  - Atomic mixing at the bonding surfaces, resulting in intermetallic compounds with altered wettability characteristics and with different thermomechanical properties
  - Microstructural changes
    - formation of dislocations and void networks which reduce electrical and thermal conductivity
  - Creep
  - Embrittlement of the solder (could lead to cracking)
  - Transmutation product formation (such as helium)
    - reduction of the ductility of the bonding material, particularly if operational at low T (200–300 °C) where the radiation damage is not annealed out rapidly
    - swelling of the solder
  - Waste disposal
- Component design and integration issues
  - Coolant flow and temperature distributions
  - Mechanical attachment to the support structure
  - Remote maintenance (installation or replacement)

evaluation, together with parallel design model development/validation. Each screening phase is used to systematically reduce the number of test options that go forward so that the more involved tests are effectively utilised. Model development ensures that validated design and analysis tools are available for final ITER hardware definition. The screening phases are followed by prototype component design, fabrication, testing, and model validation phases. The prototype design and fabrication is sequenced to take full advantage of the screening test results as well as those from an added fabrication/repair process development task. The latter task assures that the thermal bond attachment process is ready for large-scale application and that remote repair considerations are addressed in the prototype design. Finally, neutron irradiation and post-irradiation testing are spread across the screening and prototype testing phases. This permits early identification of fundamental radiation-induced problems so that resistant options are selected for the prototype components.

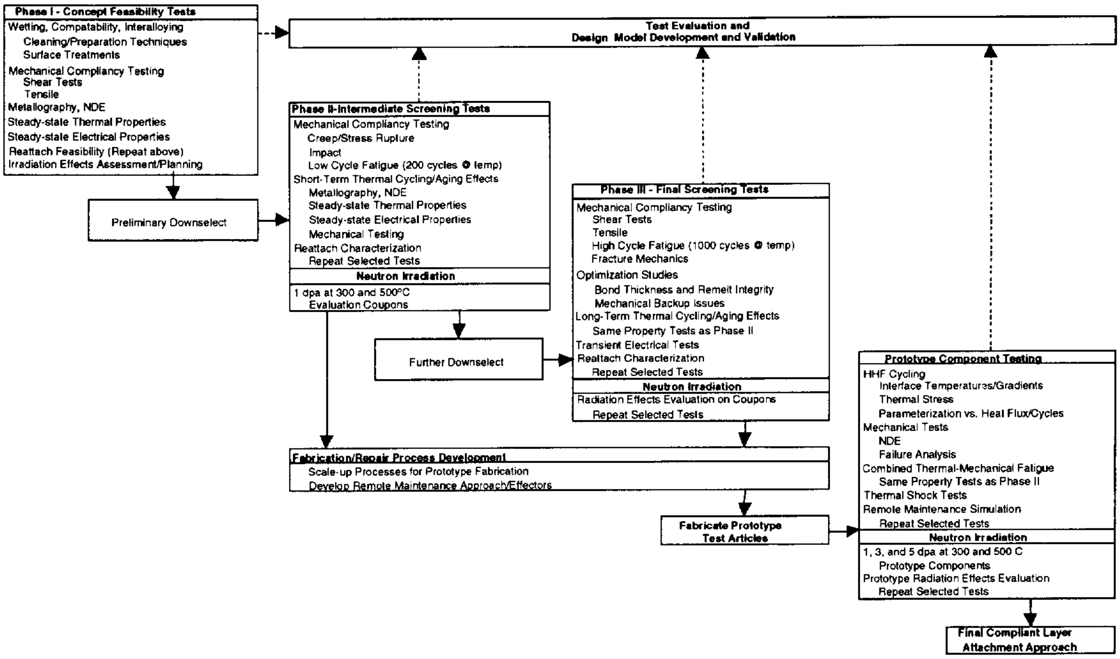

Fig. 4. R&D plan for thermal bond materials.

A key aspect of the prototype component fabrication and testing phase involves validating the proposed production processes and associated quality assurance procedures. This will include a review of inspection techniques and defect database scale-up issues relative to maintenance assessments for in-service components. The maintenance approach will also be validated. This is facilitated through the production and testing of several small-scale components. The fabrication must be as prototypical as possible to the final production environment to validate feasibility of scale-up. Furthermore, the number of articles must provide a statistically significant sample for evaluating reliability and production cost. The test articles must also be compatible with neutron irradiation capsule sizes and hot cell facility capabilities to enable parallel evaluation of irradiated prototypes. Finally, the test articles must include an interface with, and the design of, remote maintenance effectors to permit an assessment of the maintenance approach during testing.

The result of this activity will be a validated thermal bond attachment approach for ITER plasma-facing components. This will include a set of design guidelines and analysis tools, production-worthy fabrication processes and controls, quality assurance techniques and procedures, and an initial definition of remote maintenance effectors and procedures. The phased test plan will ensure that a reliable and cost-effective thermal bond attachment approach is selected and that it satisfies the established design and performance requirements. The emphasis on fabrication and repair process development assures that in-situ refurbishment objectives are met.

6. Summary

This paper presents a novel idea for the interface joint between the sacrificial armour and the actively cooled permanent heat sink which consists of a thermal bond of solder or braze alloy in the rheocast condition. These alloys in the "mushy state" exhibit a time-dependent, shear rate-dependent viscosity, which is maintained reversibly when the material is solidified and heated again in the semi-solid state. Their function is to facilitate heat transfer between the replaceable armour and the permanent heat sink without building up excessive thermal stresses, as in conventional brazed joints, and allow an easy replacement, whenever needed, without disturbing the coolant system. No contact pressure is required in this case to provide the desired heat transfer conductance and the reversible thixotropic properties of the rheocast material should guarantee the stability of the layer in the semi-solid conditions.

After a preliminary assessment, several material candidates for a compliant interface layer have been identified, consistent with all of the design and operating constraints imposed in ITER. Initial thermal–mechanical analyses indicate that adequate heat transfer can be maintained even with substantial debonding, provided initial wetting is good. Many critical design and material issues have been identified and discussed in this paper. A complete R&D programme has been defined which will provide sufficient information to assess the feasibility of the concept over four years, consistent with the schedule of ITER.

Acknowledgement

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