In-Situ Repair Concepts for the ITER First Wall Components

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The ITER General Design Requirements call for a design allowing the in-situ repair of protective armours and, if possible, the separate replacement of FW sub-components, in order to minimise intervention time and radioactive waste generation. The technologies necessary to implement this maintenance strategy and the relevant experimental results of the on going ITER R&D program specifically tailored for their development are discussed in this paper.

1. INTRODUCTION

Plasma interaction during normal and off-normal events is likely to damage the First Wall (FW) at different levels, i.e. a) protective armour, b) heat sink and c) shield structure. As far as practical, FW components will be designed to limit the extent of damage and thus minimise the repair/replacement operation. This also would reduce rad-waste produced during maintenance, as well as the overall maintenance time. Erosion due to sputtering, plasma disruption, Vertical Displacement Events (VDE) and power transients will progressively reduce the thickness of the armour and eventually damage the underlying structure [1]. Depending on the extent of the damage, the maintenance scenario contemplates various operations of increasing complexity: 1) In-situ repair of the damaged/eroded armour; 2) In-situ replacement of damaged FW sub-component; 3) Replacement of the whole FW/Shield module.

For the first operation, in-situ repair of the Be protective armour, several coating technologies have been evaluated. Low Pressure Plasma Spray has been selected as reference method on the basis of coating quality, deposition conditions and expected in-service performance.

The second one, replacement of damaged sub-components, relies on possibility of in-situ re-brazing a sacrificial armour thermally bonded to the permanent water cooled heat sink via a “Thermal Bond Layer” (TBL) [2]. The functions of the TBL are: 1) assure a good thermal contact between armour and heat sink, 2) be compliant for reducing the interface thermal stress. The aim of this paper is to discuss the choice of the method for in-situ repair of protective armours and the feasibility of integrating into the design of Plasma Facing Components (PFC) a replaceable sacrificial sub-component to allow a faster repair in case of severe damage. Two specific cases will be considered, the Primary Wall (PW) and the divertor Dump Plate (DP).

2. COATING TECHNOLOGIES

The following coating technologies have been investigated as possible methods for repairing the metallic armour of low and medium heat load PFC:

- a) Low Pressure Plasma Spraying (LPPS) [3],
- b) Rotating Rod Arc (RRA) [4],
- c) Vacuum Arc Deposition (VAD) [5],
- d) Physical Vapour Deposition (PVD) [6].

Table 1 summarises for Be the main achievements and the state of art of the four techniques under scrutiny. The coating is required to have high adhesion to the substrate (the armour materials itself), high thermal conductivity, adequate neutron irradiation resistance, good mechanical behaviour under cyclic heat loads and thermal shocks, high deposition efficiency and, finally, low tritium permeation and inventory.

Surface preparation techniques to remove oxides or other contaminants present on the plasma facing
surface prior to the coating and post-deposition surface conditioning treatments using high energy beam sources (i.e. e-beam, laser, plasma), which could lead to considerable improvement of the coating quality, have also to be developed, taking into account the constraints of an in-situ operation.

With the exception of RRA, all methods have proven to yield high density coatings, approaching the theoretical density.

The coating thermal conductivity has been measured only for LPPS and PVD. The values are excellent for LPPS, practically coincident with thermal conductivity of bulk beryllium in the temperature range RT-600°C. In the temperature range RT-400 °C, PVD produces coatings with a constant thermal conductivity of 120 W/m K.

The adhesion of beryllium coating to a beryllium substrate is high in LPPS, reported values of 4-pt bend strength in the range of approx. 110-200 MPa were recently obtained. No measures are available for RRA and PVD, but on the basis of metallographic observations and of thermal fatigue experiments it can be concluded that is rather low. For VAD the adhesion exceeds 30 MPa, the limiting strength that was possible measuring with the method used.

LPPS and RRA have the highest deposition rates, 4 and 0.4 Kg/hr, respectively. Coating thicknesses of the order of 10 mm can be readily obtained. The deposition rate of PVD and VAD is low, 0.2 and 0.030 mm/hr, respectively. For in-situ repair the thickness of Be coating to be restored is of several mm, corresponding to a very long refurbishing time for VAD. Optimisation of the VAD technique to increase the deposition rate is under way.

The deposition efficiency (coating mass/mass of feed stock material) is claimed to be 100% for PVD and VAD. This datum has to be confirmed by actual measurements. For LPPS of beryllium an efficiency of ~65-80 % has been already measured. A recent paper on advances in plasma spray techniques shows that for the deposition of metals an efficiency of over 90% is possible with axial injection plasma spray [7]. RRA has the lowest deposition efficiency, less than 50%.

The available results for LPPS and PVD have been obtained with a substrate temperature in excess of 500°C, a temperature exceeding the requirements for an in-situ repair operation, if heating involves the whole heat sink. If heating is limited to a thin surface layer, these limits can be reconsidered. However, in dealing with irradiated materials, one has to stay in any circumstances below the He embrittlement temperature of the substrate. A low, undetermined substrate temperature is indicated for RRA; VAD works at temperatures in the range 100-300 °C. The low substrate temperature represents a clear advantage over the other methods.

A limited number of thermal fatigue experiments were carried out on beryllium coatings. Two tests

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Table 1  Be coating technologies investigated

<table>
<thead>
<tr>
<th></th>
<th>LPPS</th>
<th>RRA</th>
<th>VAD</th>
<th>PVD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residual porosity</td>
<td>~2</td>
<td>high</td>
<td>~3-3.5</td>
<td>~1</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>up to 190</td>
<td>poor</td>
<td>fair</td>
<td>up to 120</td>
</tr>
<tr>
<td>Bond Strength</td>
<td>110-200* on Be</td>
<td>poor</td>
<td>on Be &gt;30 (shear)</td>
<td>poor</td>
</tr>
<tr>
<td>Substrate temperature</td>
<td>&gt;500</td>
<td>not avail.</td>
<td>100-300</td>
<td>500-600</td>
</tr>
<tr>
<td>Substrate preparation</td>
<td>negative transfer arc</td>
<td>mechanical grinding</td>
<td>glow discharge</td>
<td>none</td>
</tr>
<tr>
<td>Deposition rate</td>
<td>mm/hr Kg/hr</td>
<td>4.5</td>
<td>0.4</td>
<td>0.03-0.3</td>
</tr>
<tr>
<td>Thickness</td>
<td>mm</td>
<td>&gt;10</td>
<td>&gt;10</td>
<td>0.4</td>
</tr>
<tr>
<td>Deposition efficiency</td>
<td>%</td>
<td>65-80 (90)</td>
<td>&lt;50?</td>
<td>100?</td>
</tr>
<tr>
<td>Thermal fatigue</td>
<td>MW/m2/No. of cycles</td>
<td>5/680</td>
<td>not tested</td>
<td>not tested</td>
</tr>
<tr>
<td>Industrial capability</td>
<td>Well developed and fast growing</td>
<td>Developed for Be pellets production</td>
<td>Developed for thin coatings</td>
<td>Well developed for thin coating</td>
</tr>
</tbody>
</table>

*4 points bend strength;   # >2 with thermal treatment at 800°C
were performed on beryllium plasma sprayed coatings which were applied to both a damaged and undamaged surface of an ISX-B beryllium limiter tile [8]. Results showed that the performance of the beryllium coating was substantially influenced by the condition of the surface to be coated. The LPPS beryllium coating of an undamaged tile survived 80 cycles at 5 MW/m² for 10 s pulses before cracking was observed in the coating, which lead to the formation of hot spots on the surface. The beryllium coating that was applied to a badly melted tile survived 500 cycles (same conditions) before cracking was observed and a total of 680 cycles before the formation of hot spots on the coating surface terminated the test. It is worth mentioning that the beryllium spray process was not completely optimised for this demonstration. One test was carried out on a PVD coating 1.8 mm thick, which survived only several cycles at ~2 MW/m² before the coated layer delaminated. The poor performance of PVD coating is attributed to the lack of adequate surface preparation. The widely different HHF results obtained for the three surface conditions prior to LPPS and PVD demonstrate the importance of this parameter.

3. THERMAL BOND LAYER

The TBL concept is based on the presence of a rebrazeable soft compliant layer between the armour and the heat sink. During operation, the TBL has to efficiently transfer the heat without constraining the relative displacement due to the thermal expansion mismatch of the two different materials. Some necessary conditions have to be fulfilled: adequate bond strength, higher than the flow stress of the TBL material, large ductility, metallurgical compatibility with both armour and heat sink materials, stability in any operational condition, reversibility of the bonding process.

The TBL investigated by the four Home Teams were liquid Ga or Pb [6,9], infiltrated felt [10], rheocast Cu-Pb monotectic [11]. Only the results of the TBL’s which reached the “proof-of-principle” stage will be discussed here, i.e. the rheocast Al-Ge eutectic [12] and the Pb solder [9] TBL’s.

The rheocast processing technology [13] consists in vigorously stirring a two phases alloy featuring a large solidification interval 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 rheocast alloy has a number of features which makes it potentially interesting as TBL. When heated above the solidus temperature, the rheocast alloy transforms into a semi-solid having a viscosity close to that of grease. This property allows the in-situ replacement even on a vertical surface. Moreover it allows the fabrication of thick joints (0.5–1 mm) with obvious advantages from the point of view of thermal stresses and geometrical tolerances. This property is reversible with temperature, the globular structure and its rheological properties being retained after multiple solidification and partial re-melting cycles, provided the rheocast treatment temperature is not exceeded.

The Al-Ge system was chosen by the CEA on the basis of operating temperature range, wettability, compatibility and ductility considerations. The rheocast Al-27.6wt%Ge alloy was fabricated in form of sheets and thoroughly characterised [14] (tensile and creep tests in the solid state, compression tests in the semi-solid state, metallography of the interface with copper and its evolution with temperature, mechanical resistance of the joint, removal and replacement of copper plate). Re-brazing experiments were carried out at 475°C, ~50°C above the solidus temperature (424°C). During this experiments, the brazing alloy reached the semi-solid viscous state without flowing down. The joint between the new Al-Ge sheet and the debrazed part could not be detected by metallographic analysis. The UTS is of ~190 MPa at RT and decreases to ~13 MPa at 400°C. In the same temperature interval the fracture strain increases from 5 to over 90%. The creep rate is ~10⁻⁶ at 300 °C under a stress of 10 MPa. Shear tests at room temperature on several Cu/Cu sandwiches with various brazing thicknesses (0.15–0.74 mm) showed an average ultimate shear strength of ~25 MPa. The formation of a continuous Ge-rich layer near the copper interface, due to the local Al-Cu reaction and Al depletion was responsible for this low value. In order to get rid of the continuous Ge layer, the Ge content was reduced to 21.8 wt%, with an improvement of the shear strength from 25 to 75 MPa.

The measure of the thermal conductivity and specific heat of Al-Ge alloys was performed by ENEA [15]. The thermal conductivity and specific heat of Al27.6wt%Ge are ~50% and ~75% of those of pure aluminium, respectively. The reduction of Ge content to 21.8 wt% improves also the thermal
conductivity of over 25% in the expected temperature operating range. Drawing tests were carried out by the same laboratory to form the alloy sheet in the required shape. The sheet can be easily formed at 430 °C under the weight of a stainless steel punch onto a copper die in form of hemispherical dome of 30 mm diameter, 0.5 mm thickness.

A thermal fatigue test on a Cu/Cu mock-up, brazed with the non-optimised alloy, was performed by CEA with the following results: a) calibration with a heat flux increasing up to 7.5 MW/m²; water inlet temperature 100°C; b) thermal fatigue at 5.6 MW/m² for 26 cycles. The test was terminated due to damage near one edge, at the cold Cu interface [14]. It is worth noting that these results were obtained with the first rheocast alloy, having a bond strength of only 20 MPa, as compared to the 75 MPa of the optimised braze. Extrapolating these results to the real geometry and heat loads, it is reasonable to assume that the optimised joint can withstand the design number of cycles and the loads of the primary wall (0.5 MW/m²).

4. DESIGN

The application of the TBL concept to two plasma facing components, the Primary Wall and the divertor Dump Plate, is at present being evaluated, both analytically and experimentally. The most critical design condition for the PW is the heat load during a VDE (20-60 MJ/m², 0.3-1 s). With the progressive reduction of the beryllium tile thickness, as a consequence of the various erosion mechanisms, higher and higher temperatures may be attained in the copper heat sink and at the armour joint. For an armour residual thickness of 5 mm, the temperature at the joint can exceed 700°C, with an increasing failure probability, either of or of the Be/Cu joint or the heat sink. In the present design, the only line of defence is the timely refurbishing of the armour by plasma spray. It is worth exploring the possibility of having a second line of defence against VDE, to avoid the replacement of the entire shielding blanket module in case of severe damage.

A representative mock-up of the separable wall shown in Fig. 1 is being fabricated with the rheocast technology. It will be tested under normal and off-normal heat loads.

Two alternative designs of the replaceable sub-component are possible, one (D1) made out entirely of beryllium, the other (D2) with a beryllium tile bonded on the top of a copper T-shaped element. The former design is much simpler, avoiding the additional Be/Cu joint. However, it has to be assessed whether the replacement operation of the sub-component is compatible with the beryllium embrittlement after neutron irradiation at the expected operating temperature.

Since the liquidus and the brazing temperature of Al-21.8wt%Ge are relatively high, 427 and ~525°C, respectively, the problem of heating the old subcomponent for in-situ removal and the new one for rebrazing in not trivial.

One possible method is the use of High-Energy Electron-Beam (HEEB) processing [16] with energies in the 1-10 MeV, in pulses of 10-10⁴ ns duration in beams of centimetre diameters. HEEB can be operated in air or inert gas, because of the reduced beam spreading by the atmosphere. Since the energy deposition of the HEEB is proportional to the atomic number of the elements, the replaceable beryllium (Z=4) sub-component would be rather transparent to the beam, with maximum absorption of energy in the rheocast layer (effective Z=17) and in copper (Z=29). The energy distribution should be sufficient to heat the braze and the substrate without overheating the beryllium tile.

For the divertor dump plate, the most severe design condition is the slow, high-power transient from 5 to 20 MW/m² in 10s. Here the issue is not so much the in-situ replacement, because the whole
A divertor is designed for a rapid replacement of all HHF components outside the plasma chamber, but the protection against burn-out phenomena and against damage propagation from the armour to the heat sink during off-normal events, the ease of tile replacement, the reduction of rad-waste. A mock-up (Fig. 2) with a pyramidal CFC tile joined to a water cooled copper heat sink by a 0.5 mm thick Pb0.1%Cu braze, was high heat flux tested with the following results: 50 cycles at 5 MW/m$^2$, water inlet temperature 25°C, burn duration 30 s, 30 additional cycles at 10 MW/m$^2$ without any sign of degradation [17]. Since the Pb braze partially melts at the higher heat flux, the use of this solution is limited to a horizontal target such as the inboard short dump target of ITER.

After having ascertained the thermo-mechanical performance of the Pb TBL, the problem of its stability above the Pb melting point will be addressed. The envisaged solution of the melted braze stability relies on the use of a rheocast Pb-Cu alloy [11] or of a Ni felt infiltrated with liquid metal [10].

5. ANALYSES

A 2D thermomechanical analysis of a separable PW mock-up (D2 option) was performed to evaluate the temperature and the elastic stress distribution when a heat flux of 0.5 MW/m$^2$ is applied in steady state test condition. Generalised plane strain (with free rotation) boundary condition has been applied out of plane. Other input data were:
a) water inlet temperature 140 °C;
b) heat transfer coefficient 16000 W/m$^2$·°C;
c) water pressure 4 MPa;
d) stress free temperature 20 °C.

The maximum temperature in the TBL is 193 °C. The presence of the rheocast alloy has a small influence on the temperature distribution in the structure, because its relatively large thermal conductivity and small thickness.

Thermal stresses arise in the rheocast alloy region already at the coolant temperature with no heat flux due to the mismatch in the thermal coefficient of expansion. These are mainly in longitudinal direction (max. -38 MPa). The maximum Von Mises elastic stress when the heat flux is applied is 71 MPa, as shown in Fig. 3.

The stresses due to the coolant pressure are negligible. In the real structure a decrease of stresses is expected because of the castellation in longitudinal direction.

To judge whether this stress can be considered acceptable with good engineering margins, a plastic analysis would be needed. However, the very function of the TBL is to accommodate the differential expansion by a small plastic deformation (to be compared with the ductility of the material, as high as 40% at 200 °C) to relax the thermal stresses.

By comparing the present FEM results with those of the reference PW design, it can be inferred that the TBL does not change appreciably the stresses level in copper and stainless steel.

A second analysis was conducted to evaluate the thermal response of the separable first wall against the thermal transient expected to take place on the primary first-wall, during accidental plasma contact during burn, e.g., resulting from VDE (≤ 60 MJ/m$^2$ in times of 100 ms -1s) The model RACLETTE [18,19] was used to perform the calculations. It provides for the solution of the heat conduction...
problem across a duplex structure and includes evaporation, radiation, melting of the armour material and convective heat removal at the coolant side. The model is based on a simple 1-D geometry, corrected to account for two-dimensional effects in the case of a circular cooling channel. Two cases were analysed, first, referring to option D1, second, referring to option D2. The results of the D1 analysis are shown in Fig. 4; D2 gives similar results. The temperature of the two characteristic points of the TBL (indicated as T1 and T2 in the figure) is plotted considering the armour thickness at the beginning-of-life (BOL), i.e., 10 mm, and at the end-of-life (EOL), 8 mm. During the transient, the rheocast braze is overheated above the solidus for 2 s at BOL and for increasing time as the armour erodes. During this short permanence in the semi-solid state, the attachment of the subcomponent to the heat sink should be provided by the vertical leg sitting between the cooling channels, which remains in any circumstance solid.

Preliminary calculations were performed to check the capability of the proposed separable PW to withstand the electromagnetic loads during off-normal events. During plasma abnormal transient, e.g. disruptions or Vertical Displacement Events, we expect an electromagnetic pressure on the PW up to 1.2 MPa (directed towards the plasma) and up to 3 MPa (directed towards the blanket module); the contemporary presence of mechanical and thermal loads due to the large energy deposition has to be considered. In this conditions, as shown by the VDE analysis, the rheocast TBL is above the solidus temperature along the surface of the model; therefore only the joint along the radial rib of the structure can have structural functions. Even in this case, no additional mechanical attachment is needed, if the shear strength of the bond is above 5 MPa, value to be compared with the measured shear strength of the Al-Ge TBL of 75 MPa at RT.

6. SUMMARY

Different technologies are under development to allow the in-situ maintenance of PFC’s, according to the extent of damage caused by their interaction with the plasma:
- coating methods for in-situ repair of the erosion or local damage of the tiles;
- in-situ rebrazing of separable sub-components to avoid replacement of a whole FW/Shield module in case of loss of tiles or damage to the underlying structure.

As far as the first operation is concerned, LPPS is by large the most suitable coating technique for in-situ repair. It fulfils all in-situ repair requirements but one, the substrate temperature during the deposition process, that is still to high. VAD presents some advantages in term of substrate temperature and deposition efficiency. It could be considered as a back-up solution, pending an experimental proof to produce coatings of relevant thickness and adequate thermal fatigue lifetime.

For the in-situ rebrazing, the encouraging results obtained in the development of the TBL concept allow to consider alternative designs of the PFC, under experimental validation, which will shorten the replacement time and reduce the rad-waste.

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