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Section 14. Joining and welding of metals

Overview on fabrication and joining of plasma facing and high heat flux materials for ITER

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Abstract

This paper presents the results of the R&D program on the development of the joining technologies, including non-destructive inspection, for the high heat flux components carried out by the three ITER Participating Teams. Reliability requirements and design criteria are also discussed. The large amount of R&D performed within the ITER project has resulted in the development of suitable technologies, which meet or even exceed the design requirements and form a solid basis for the possible future construction of the ITER machine. However, further developments are still needed for the consolidation of the positive results with improving the reliability of the joints and reducing the manufacturing cost.

1. Introduction

The development of the ITER high heat flux (HHF) components, namely the divertor and the port limiter, represents one of the most challenging engineering effort ever made in the scientific field. The general configuration of a HHF component consists in an armour material, which directly faces the thermonuclear plasma, and in a so-called ‘heat sink’, which transfers the heat loads from the armour to the water coolant. The armour to heat sink joint appears the most critical manufacturing step upon which mainly depend the heat removal capabilities and the thermal fatigue performances of a HHF component. To avoid poisoning of the cryo-pumps, elements with high vapour pressure, e.g. zinc or cadmium, are not allowed as brazing/filler materials, nor those which form the same elements by neutron transmutation, such as silver or gold.

As far as the divertor is concerned, two different joints are actually required between the armour and the heat sink. In fact a pure copper (Cu) interlayer must be envisaged to accommodate the thermal expansion mismatch. The first joint is between the armour material, namely tungsten (W) or carbon fibre reinforced carbon (CfC), and the pure Cu interlayer. The second one is between the pure Cu and the heat sink, namely the precipitation hardened copper–chromium–zirconium (CuCrZr) alloy.

The lower part of the vertical target intercepts the magnetic field lines and has to remove the heat load coming from plasma via conduction and convection during the normal and transient operation as well as during the off-normal events. CfC is the reference design solution for the armour in this region. In fact it is a very forgiving material with respect to the expected high heat loads due to its absence of melting, to its high thermal shock and thermal fatigue resistance (low crack propagation) and to its high thermal conductivity in comparison with conventional graphites.

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Table 1
Main operating conditions of the ITER HHFCs [4–7]

	Divertor target	Port limiter
Normal operation		
Peak surface heat flux (MW/m^2)	10 (on CfC) 0.1–5 (on W)	8 (during start-up and shut-down)
Duration (s)	<450	<50
Number of cycles (without replacements[a])	30 000	60 000
Peak particle flux (10^{23}/m^2 s)	∼10	∼0.01–0.1
Off-normal operation	Slow transient	–
Peak surface heat flux (MW/m^2)	20 (on CfC)	–
Duration and frequency	10 s/10%	–
Disruptions	Thermal quench	Thermal/current quench
Peak surface heat load (MJ/m^2)	10–30	1 (TBD)
Duration and frequency	0.1–3 ms/10%	0.1–3 ms/10%
VDE (full power)		
Peak surface heat load (MJ/m^2)	60	–
Duration and frequency	100–300 ms/1%	–
Max radiation damage at 0.3 MW/m^2 (in dpa, without replacements[a])	0.7 (in W) 0.7 (in CfC) ∼2 (in Cu)	1 (in Be) 3 (in Cu)

[a] 3–5 replacements are envisaged for the divertor and the port limiter.

The main design option foresees CfC monoblocks (i.e. CfC blocks with a cooling channel obtained by drilling). The CfC armour thickness is typically of 15–20 mm.

W/Cu joints are envisaged for the upper part of the vertical target and for the dome. W is the preferred armour material due to its lowest sputter yield in regions where resistance to charge exchanged neutrals dominates and due to the need of minimising the tritium inventory. Furthermore W has the highest melting point of all metals, the lowest vapour pressure, and a good thermal conductivity.

The main design option foresees an array of W tiles (the so-called 'macro-brush'), but the use of W tiles in the form of monoblocks is also under consideration. The W armour thickness is typically of 10 mm. The application of the tungsten plasma spray technology is also foreseen to protect the side surfaces of the dome, which are not directly exposed to the plasma [1].

As far as the port limiter is concerned, beryllium (Be) is the ITER reference armour material. Its choice is mainly dictated by the need to avoid carbon materials above the X-point of the magnetic field lines thus confining the concerns on tritium codeposition to the divertor area. The main design option uses Be flat tiles from sintered blocks, which are bonded to the Cu alloy cooled structure. The typical thickness of the Be armour is 4–5 mm [2]. The plasma spray technology could also be used for the manufacturing and repair of the components [3].

The reference copper alloy for the port limiter is the precipitation hardened CuCrZr or the dispersion strengthened CuAl25-IG (DS-Cu).

Table 1 shows the main operating conditions of the armour to heat sink joints for the HHF components. Due to the high cyclic heat loads, thermal fatigue is, together with armour erosion, the most lifetime limiting phenomenon and the experimental results have confirmed that the detachment of the armour is the most likely failure mode.

This paper presents the main results of the R&D program on the development of the joining technologies for the HHF components carried out by the three ITER Participating Teams, namely the European Union (EU), Japan (JA) and the Russian Federation (RF). Reliability requirements, non-destructive inspections and design criteria are also discussed.

2. Armour to heat sink joints

2.1. CfC/Cu joint

Among the available CfC grades, the 3D CfC SepCarb® NB31 (produced by SNECMA, France) [8] and NIC-01 (produced by Nisseki-Corporation, Japan) have been selected as the Ref. [9].

The main problems in the development of the CfC/Cu joints are the large thermal expansion mismatch, which generates high joint interface stress during manufacturing and operation, and the fact that Cu does not wet carbon, which prevents direct casting. The first issue is handled by means of a pure Cu soft interlayer between the CfC and the CuCrZr heat sink, whereas the absence of wetting is overcome by a proper activation of the CfC surface prior to casting or by using a brazing alloy with good wetting characteristics.

The monoblock geometry has been selected as reference for the CfC armour to be used in conjunction with Active Metal Cast (AMC®) for the CfC/Cu joint. The monoblock is preferred over the less expensive flat tile design, because of concerns over the observed tendency for flat tiles to suddenly and totally detach [10]. For the AMC® joint the bores of the CfC monoblocks are lined with a pure Cu layer cast onto a laser-textured and titanium activated surface [11]. The main advantages of the AMC® technology are its high re-melting temperature (1083 °C) and its excellent reliability.

Possible alternatives to the above-mentioned joining technique have been developed in JA using Cu–Mn brazing [12] and 15Cu–25Ni–60Ti with fast quench [13].

2.2. *W/Cu joint*

Pure sintered W is recommended as the reference material for divertor components. This material is widely available from different suppliers. The W properties database is also well established.

One of the most studied technology is the casting of pure Cu onto W (EU and RF) [14,15]. The wetting contact angle is zero at a temperature more than 1350 °C, that means full wetting. However, at temperature higher than ~1200 °C, recrystallization of W starts for most of the W grades. For this reason the maximum process temperature is limited to ~1200 °C. The purity of the Cu used for the casting process plays an essential role for producing high quality bonds.

The RF has also studied the brazing technology. Cu–Mn-base brazing alloy has been selected as the most suitable for the joining of the W onto the Cu. As example, the brazing alloy with compositions 72 Cu%; 25 Mn%; Fe, Si, Ni up to 1% (with a typical brazing temperature of ~900 °C) has shown good wetting characteristics [15].

JA has further developed the direct hot pressing of the W rods previously investigated in the USA [16]. The best tensile strength of the W/Cu joint was achieved at 900 °C, with a special groove at the end of the W rod [17].

For low heat flux loaded W armoured components, the EU Team has developed and tested the W plasma spray technology [18].

2.3. *Be/Cu alloy joint*

Experiments based on the thermal fatigue resistance and thermal shock experiments indicated that the most resistant Be grades are S-65C 'vacuum hot pressed' (Brush Wellman, US) and DShG-200 (RF).

S-65C grade has been selected as a reference grade due to its lowest BeO and other metallic materials impurities content, high elevated temperature ductility, better database and availability [19]. DShG-200 was retained as a back-up [20].

Differently from CfC and W armour, Be is usually joined directly onto the Cu alloy heat sink without a pure Cu interlayer thanks to the fact that its thermal expansion coefficient does not differ significantly from that of Cu. The main problem of bonding Be to Cu alloys is that Be reacts with almost all metals and forms brittle intermetallics.

Among the different approaches that have been studied to prevent an extensive formation of brittle phases and provide a good quality of Be/Cu joints, the following two strategies have been most successful:

- use, as diffusion barriers, materials with less affinity to the formation of intermetallics;
- use, as fillers or interlayers, materials that interact with Be (e.g. Cu, Cu based brazing alloys), but control the formation of the intermetallics by a proper selection of process parameters.

The EU has studied the use of titanium (Ti) as diffusion barrier material. For this type of joint HIP'ing is used as joining procedure at a temperature range of 500–850 °C. The use of a Ti interlayer with a few hundreds micron coating of pure Cu and HIP'ed at 580 °C, 60 MPa, 2 h seems promising [21].

The RF has developed a fast brazing technology using Cu–In–Sn–Ni, Cu–Ni–P and Cu–Mn alloys. All these fillers have been applied together with fast heating. This fast brazing technology has been used for the manufacturing of more than 20 mock-ups with excellent thermal fatigue capabilities. The fast brazing is achieved by using an electron beam. The heating time from 450 °C up to 800 °C is ~2–3 min, cooling time from 800 °C down to 450 °C is ~8–10 min, exposure at 800 °C is 5–10 s. Because of the short time, the process is compatible with CuCrZr. By means of hardness measurements it is estimated that after fast brazing the ultimate strength of CuCrZr can be as high as 350 MPa (at RT) [22].

2.4. *Cu/CuCrZr joints*

Differently from the armour to pure Cu joint, in this case the joining heat cycle has to be compatible with the overall manufacture process of HHF components and in particular with the requirement to maintain adequate thermomechanical properties of the CuCrZr alloy. Several technologies have been developed.

For the flat tile design, the EU has developed the electron beam welding of the Cu layer onto the cooled heat sink. The use of electron beam does not effect the bulk properties of CuCrZr [23]. JA has HIP'ed the pure Cu interlayer onto the CuCrZr at low temperature at 480 °C, 60 MPa [17].

For monoblock tiles, a low temperature HIP technology has been developed by the EU. The HIP process is carried out at 550 °C, 4–6 h, starting from solution annealed water quench and cold worked CuCrZr tubes, which are then aged during the HIP cycle. After this heat treatment, CuCrZr has good mechanical properties (tubes with ultimate tensile strength between 350 and 500 MPa at RT have been obtained). This technology has been applied for manufacturing straight and curved mock-ups.

Other options such as fast-brazing or conventional brazing followed by a fast quench could be cheaper alternatives and their viability is being investigated by all the three ITER Parties. JA and EU have developed the brazing with fast quench for Cu/CuCrZr joint. In this process, the silver free filler Cu–Ni–Mn is used [17]. The RF has also developed the brazing with fast quench using Cu–In–Sn–Ni (STEMET 1108) filler [15].

3. High heat flux test results

3.1. Components with CfC armour

The EU has manufactured and tested several mock-ups with flat and monoblock type of CfC armour using AMC®. A divertor prototype sustained 20 MW/m^2 × 2000 cycles on the CfC monoblock region plus a few critical heat flux tests in excess of 30 MW/m^2 [24] (Fig. 1). Another CfC monoblock endured 1000 cycles at 19 MW/m^2 plus 680 cycles at 23 MW/m^2. A CfC flat tile was tested for 1000 cycles at 20 MW/m^2 and 430 cycles at 23 MW/m^2 before failure. A small-scale mock-up (made of CfC Dunlop Concept 1 armour AMC® onto a DS-Cu tube) was irradiated at 0.35 dpa at 350 °C and then loaded at 15 MW/m^2 per 1000 cycles without failure [25].

JA has manufactured and tested several CfC armoured mock-ups with saddle geometry (1D and 3D CfC) and monoblock geometry. A large-scale CfC monoblock mock-ups was manufactured with annular flow using the fast brazing technique. It had an outer tube made of CuCrZr (19 and 15 mm OD, ID, respectively) and an inner SUS steel tube (11 and 9 mm OD, ID, respectively); the annular flow twist ratio was 3. It withstood 1000 cycles at 20 MW/m^2 and 3000 cycles at 15 MW/m^2 (Fig. 2).

3.2. Components with W armour

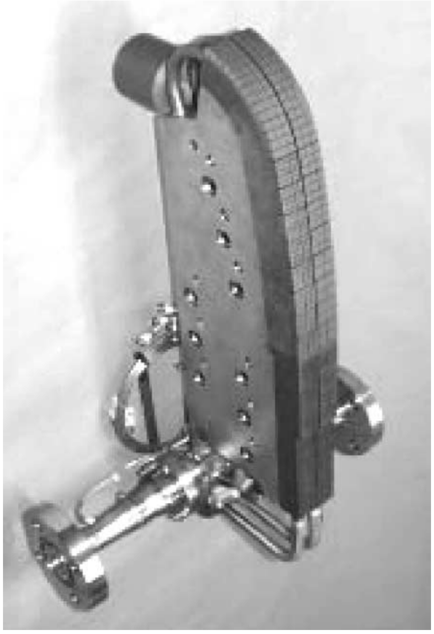

Fig. 1. EU divertor prototype with CfC monoblocks and W macro-brush armour.

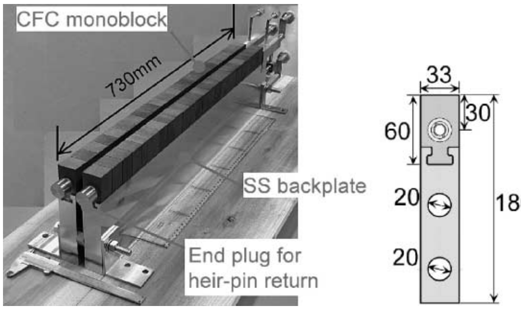

Fig. 2. JA monoblock component with annular flow.

The most successful approach for joining W to the heat sink is the combination of casting of pure Cu onto the W tiles combined with the 'macro-brush' or lamella-like structure. The HHF testing performed in the RF and EU have confirmed the excellent heat removal capabilities of these joints.

A number of W macro-brush and W monoblock mock-ups manufactured by the EU were tested for 1000 cycles at 18 MW/m^2 without failure.

Tests of the vertical target prototype with pure W and W–La$_2$O$_3$ armour tiles with different dimensions shows that there is no major difference between these W grades and large macro-brush tiles ($\sim 20 \times 20$ mm) could be used. The EU has also developed a W plasma spray technology. Mock-ups with a sprayed armour thickness of about 5 mm have survived 1000 cycles up to 7.6 MW/m^2 (Fig. 3) [14].

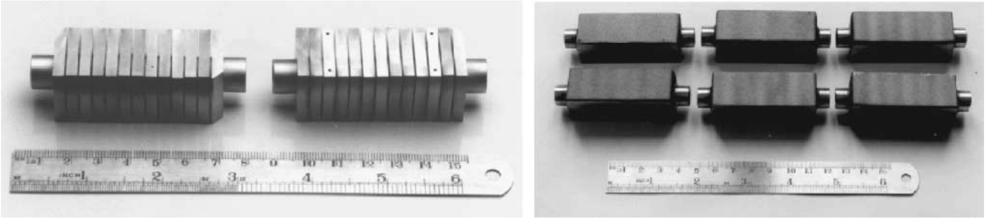

Fig. 3. W monoblocks and W plasma spray components manufactured by the EU.

W mock-up with tiles 10 × 10 × 10 mm, produced by RF survived 1000 cycles at 20 MW/m^2 and 1500 cycles at 27 MW/m^2 without any damage of the joints but only some displacements of the W tiles due to creep in the pure Cu interlayer. A large-scale mock-up with W flat tiles and hypervapotron cooling was then manufactured and successfully tested up to 1000 cycles at 18.5 MW/m^2 on 12 tiles on the straight part (Fig. 4) [26].

JA has developed a technology for the joining of the W rods onto Cu heat sink. A mock-up with rods (∅6 mm) survived 3000 cycles at 5 MW/m^2 without damage, at higher heat flux the melting of the Cu heat sink has been observed [27].

3.3. Components with Be armour

A fast brazing technique with Cu–In–Sn–Ni amorphous brazing alloy was used by the RF for the manufacturing of a number of mock-ups. The best thermal fatigue results were obtained with a macro-brush (5 × 5 × 5 mm) structure. This mock-up did not fail after 4500 cycles at 12 MW/m^2. Curved mock-ups have also been tested and no damage has been observed after 1000 cycles at 11 MW/m^2 (Fig. 5) [28].

Several mock-ups have been manufactured by EU using the HIP joining technology with a Ti interlayer. The failure limit was ∼5–7 MW/m^2, for flat tile mock-ups with cooling tubes having a stainless steel liner, and 10 MW/m^2, for Be monoblock with a DS-Cu alloy tube [21]. A brazing technology, based on the use a silver-free brazing alloy (Cu–Mn–Sn–Ce) and induction heating method was also developed. A few mock-ups withstood 1000 cycles at 5–7 MW/m^2 even after being irradiated at 0.35 dpa, 350 °C [25]. VDE simulations were also performed and metallographic examinations did not show any defects in the brazing joints due to this loading.

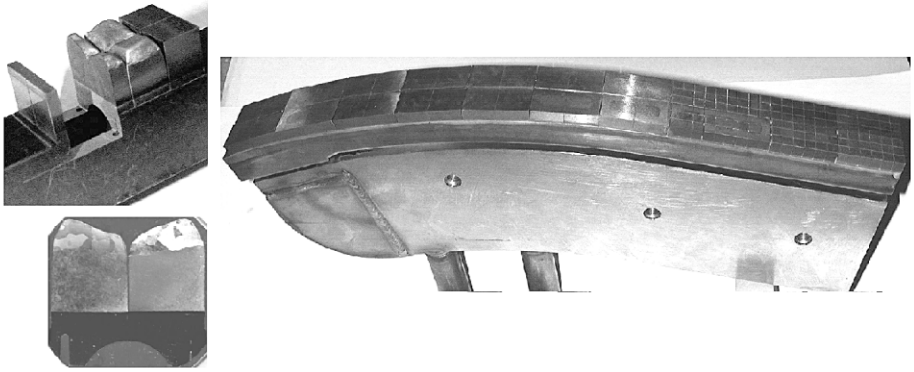

Fig. 4. W flat tile components manufactured by the RF.

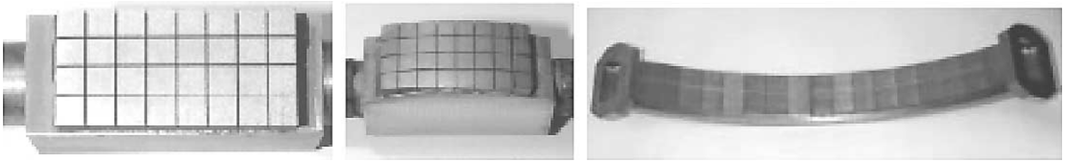

Fig. 5. Be armoured components manufactured by the RF.

4. Reliability requirements

To have an idea of the reliability requirements of the HHF components, one can refer to the vertical target, which is the most loaded plasma facing components of the whole ITER machine with its 20 MW/m^2 of surface heat flux.

In the ITER divertor there are 27 and 21 outer and inner vertical target units per cassette, respectively. Being the number of cassette 54, there are in total 1458 and 1134 outer and inner vertical target units, respectively. Taking into account that each outer and inner unit has 40 and 35 CfC monoblocks, respectively, there are in total almost 100 000 monoblocks in the ITER divertor. Assuming that during the manufacturing of the divertor the acceptance rate of the monoblocks will be around 95–97%, this means that thousands of tiles will not be bonded in an acceptable way and that, statistically, each vertical target unit will have at least one defected monoblock. Things are even worse for the upper part of the vertical target where a W macro-brush is foreseen with a number of tiles in the order of half million.

The above-mentioned considerations lead to the following conclusions:

- The reliability and reproducibility of the armour to heat sink joining technology for HHF components shall be improved up to the highest possible level.
- The maximum acceptable defects shall be carefully defined.
- The development of repairing methods during manufacturing is of utmost importance in order to avoid the rejection of valuable components and to have the whole supply delivered within a reasonable time and cost. In this respect it is worth pointing out that, if no repairing method is available and one accepts a rejection rate of 10% for the vertical target units, a monoblock reliability of almost 99.8% is required, which appears rather unrealistic at present.
- The non-destructive inspection techniques shall guarantee an early and reliable detection of defective tiles in order to enable a timely corrective action.

5. Non-destructive testing

The overall goal of the development programme on non-destructive examination (NDE) is to demonstrate that defects, which can impair the component performances, can be identified, located and sized in a reliable way. It is therefore necessary to have qualified NDE processes for all the armour to heat sink joints (CfC to Cu, W to Cu, Cu to Cu alloy and Be to Cu alloy). The selection and applicability of the different NDE methods depends on many parameters, such as armour material, shape of the interface, joining technology, etc. A survey of the different NDE applicable techniques is given hereinafter.

5.1. NDE of CfC/Cu joints

The NDE of the CfC/Cu joint is extremely difficult for the following reasons:

- Ultrasounds can hardly propagate inside the CfC material, therefore the CfC/Cu joint can only be inspected from the Cu side.
- The acoustic impedance of CfC and Cu is significantly different, therefore even a joint of good quality generates a strong ultrasonic echo.
- The AMC® technology foresees a laser structuring of the interface, which results in a very irregular shape of the joint surface. As a consequence, it is practically impossible to have any reliable ultrasonic echo.

Taking this into account, the NDE of the CfC/Cu joint mainly relies on the themographic examination. According to a study carried out by the EU, the use of this technique enables the identification of defects in the 3–6 mm range. These defects proved to be stable under HHF cyclic loads. It has been shown that the surface temperature distribution during heat flux testing is often very close to the one observed during the infrared testing [29].

Therefore the infrared thermography is a complementary and necessary NDE method which gives a global information about the soundness of the heat path thus being a fast and economical way to assess the acceptability of a component prior to its installation into a fusion machine.

5.2. NDE of W/Cu joints

The quality of the W/cast Cu joints was studied via ultrasounds. This method was used for large W tiles (40 × 40 mm) by the RF. The most frequent defects were voids (size > 1 mm) in the cast Cu, which could be easily detected [30]. The EU has carried out a round robin check of the artificial defects in a W macro-brush (5 × 5 mm) geometry. The NDE was disturbed by the macro-brush structure and by an irregular attenuation of the ultrasonic wave along the W tiles most likely due to the grain structure. The main conclusion was that the macro-brush joint should better be inspected from the rear side of the component as discussed in the next section.

5.3. NDE of Cu/CuCrZr joints

Ultrasonic inspection from inside the tube has been applied to the monoblock design. Defects with dimensions of 2 mm between AMC® Cu and the Cu alloy tube are detected reliably, and the defects with a size of ~1 mm can be detected with a good probability. These defects proved to be stable under HHF cyclic loads.

As regards flat tile components, the ultrasonic examination is better performed from the rear side rather than from the armour side. In fact, even with a W armour, the reliable detection of Cu/CuCrZr defects is impaired by the macro-brush structure of the W tiles.

A particular examination procedure must be foreseen for the ultrasonic inspection through the CuCrZr because this material features significant local differences (up to 16 dB) in the attenuation of the ultrasonic waves. Therefore a map of the sound features of the CuCrZr must be obtained and recorded prior to the Cu/CuCrZr joint is obtained.

In a study carried out by the EU several defects have been placed in the electron beam welded joint of a W macro-brush. These defects had a rectangular cross-section with the following dimensions: 3 × 11, 6 × 5, 6 × 11, 3 × 5 mm. Ultrasonic inspections of the electron beam welding demonstrated that defects having all the dimensions greater than 3 mm could be identified reliably. Furthermore the presence of large defects (up to 6 × 11 mm) in the electron beam welding did not appear to impair appreciably the fatigue lifetime of the component nor its surface temperature [31].

5.4. NDE of Be/Cu alloy joints

The ultrasonic technique for flat type tiles with size more than ~10 × 10 mm is the simplest method to detect defects with a size of ~2 mm reliably. A study carried out by the RF has demonstrated that defects with a maximum dimension of less than 3 mm in many cases have no influence on the performance of the Be/Cu joint [30].

6. Design criteria

The typical failure mode of a HHF component is the debonding of the armour to heat sink joint. Hundreds of thermal fatigue tests carried out all over the world have demonstrated that the thermal fatigue performance of a HHF component is mainly dictated by the behaviour of this joint. While a numerical analysis is always useful to make comparative assessments of different design solutions, the absolute prediction of a HHF component lifetime appears rather problematic for several reasons.

First of all, the numerical evaluation of the actual stress/strain level in the joint is not straightforward. In a flat tile geometry, the occurrence of elastic stress singularities at the interfaces requires a cyclic elastoplastic calculation. Therefore the computed stress/strain range depends on the chosen hardening rule, mesh, converging parameters and boundary conditions. However, even if the real cyclic stress/strain distribution could be properly evaluated, no fatigue curves exist on armour to heat sink joints. Their generation appears largely unpractical since the fatigue behaviour of a joint depends on a number of factors, namely: the armour material and grade, the copper grade, the joining technology (brazing, HIP'ing, ...), the joining procedure (brazing filler and brazing heat cycle, HIP can design, HIP cycle, cleaning procedure prior to join, ...), the post-join heat treatment, the component geometry and so on.

Taking this into account, the acceptability of such interfaces should be better and more reliably established by experiments. This conclusion is also endorsed by the 'ITER Structural Design Criteria' [32].

7. Summary and conclusions

Based on the results of the tests of more than 100 mock-ups and components, the following conclusion can be made:

- For the lower part of the divertor vertical target the preferred joining technique is AMC® of CfC monoblocks followed by the low temperature HIP or brazing onto the CuCrZr cooling tubes. Brazing, instead of AMC®, is retained as a back-up.
- For the upper part of the divertor vertical target the most suitable solution is brush or lamella W tiles joined by Cu casting to the heat sink via electron beam welding, low temperature HIP or brazing. The use of W monoblocks appears an attractive alternative since it would avoid the difficult monoblock to flat tile transition and would reduce the electromagnetic loads.
- For the Be armoured port limiter, fast brazing is the most performance technology. Low temperature HIP with Ti/Cu interlayer is retained as a back-up.

The 'fitness for purpose' of all the above-mentioned technologies was demonstrated on the basis of a 'design by experiment' approach, which appears the most appropriate way to assess the heat removal capability of the armour to heat sink joint. Furthermore the testing of irradiated mock-ups showed that neutron irradiation does not impair the thermal fatigue lifetime appreciably.

Suitable NDE techniques have been developed for each type of armour to heat sink joint. They proved to be able to detect different types of defects in the size range of 1–3 mm. These defects are well below those, which could impair the thermal fatigue lifetime.

The large amount of R&D performed within the ITER project have resulted in the development of suitable technologies for HHF components, which meet or even exceed the design requirements and form a solid basis for the possible future construction of the ITER machine. Nevertheless, taking into account the very large number of tiles to be joined, additional developments with the goal of the increasing reliability, repair-ability and reduction of costs appear mandatory.

In addition to that, even if the armour to heat sink joint seems the most critical manufacturing step of a HHF component, the remaining supporting structure has also a high technology content. One just needs to mention the Cu alloy/stainless steel tube to tube transition, the joints between the Cu alloy heat sink and the stainless steel supporting structure, the thousands of welds of the cooling tubes, the need to master different joining techniques into one component, the demanding requirements on leak tightness and geometrical tolerances, and so on. Therefore the integration of the armour joining technologies into a full-scale prototype represents a further and significant step towards the realisation of a reliable HHF components.

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