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Status of the beryllium tile bonding qualification activities for the manufacturing of the ITER first wall

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ABSTRACT

The preparation of the manufacturing of the ITER first wall involves a qualification stage. The qualification aims at demonstrating that manufacturers can deliver the needed reliability and quality for the beryllium to copper bond, before the manufacturing can commence. The qualification is done on semi-prototype, containing relevant features relative to the beryllium armour (about 1/6 of the panel size). The qualification is done by the participating parties, firstly by a manufacturing semi-prototype and then by testing it under heat flux. One semi-prototype is manufactured and is being tested, and further from other manufacturers are still to come. The qualification programme is accompanied by bond defect investigations, which aim at defining defect acceptance criteria. Qualification and defect acceptance programme are supported by thermal and stress analyses, with good agreement regarding the thermal results, and some insights about the governing factors to bond damage.

1. Introduction

The first wall (FW) is the main protection of the ITER vessel against the plasma. The first wall is made of 440 panels with typical dimensions of 1.5 m toroidally and 1 m poloidally, cladded with 8–10 mm thick beryllium (Be) armour tiles of 16–42 mm in size [1]. The first wall design is based on toroidal plasma facing units (the "fingers"), which are cantilevered to a structural beam oriented in the poloidal direction. The beam is the structural backbone to the first wall panel, serving both as a mechanical supporting structure and containing all the needed interfaces to the shielding blocks (water connection and distribution to the fingers, electrical earthing, remote-handling compatible attachment, see Fig. 2 in Ref. [1]). Two series of fingers on each side of the beam form two beryllium armoured wings, separated by a recessed poloidal slot giving access to the beam. The fingers have a typical length of 0.75 m. They are made of a steel/copper alloy/beryllium sandwich. The steel base of the finger has the role of supporting structure, the copper is the heat sink, and the beryllium is the armour. The water is fed through the steel, cools the heat sink, and is returned to the finger extremity through the steel base. The fingers are designed to accommodate heat fluxes from 2 (normal heat flux – NHF) to 4.7 MW/m^2 (enhanced heat flux – EHF) depending on the panel location in the first wall [1]. They are designed to 15,000 heat loading cycles. The NHF fingers rely mainly on hipped bonds, including the cooling circuit made of steel pipes and also the beryllium tiles to the heat sink. The EHF fingers are made of exploded CuCrZr to steel, and the cooling circuit is completed by welding the fabricated steel base, and the beryllium tiles are assembled by brazing. The FW has passed successfully its final design review in 2013 [2]. It is now in a pre-manufacturing phase with the preparation and signature of procurement arrangements. The FW is procured by EU (50% of the panels), RF (40%) and CN (10%) Domestic Agencies (DA) (Fig. 1).

This paper presents the qualification process that is taking place between the R&D and manufacturing phase (Section 2). In addition, Section 3 presents the parallel activities relative to the modelling of the bond behaviour with respect to the effects of defects and attempts at understanding the defect propagation criteria.

2. Qualification

The manufacturing routes towards the panel fabrication involve many challenging fabrication steps, including the bonding of the beryllium armour tiles to the copper alloy heat sink, the

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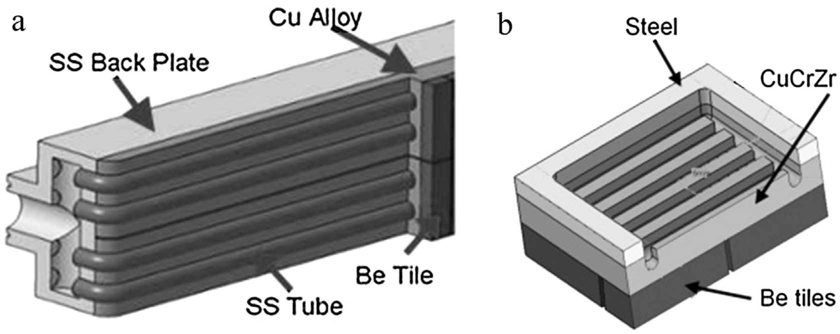

Fig. 1. Typical NHF and EHF fingers.

manufacturing of an intricate cooling circuit, integration of mechanical and hydraulical connections, isolating coatings, plus others not mentioned here. Among these delicate processes, successfully bonding the beryllium armour tile to the copper alloy heat sink is especially challenging, for two reasons: (1) beryllium and copper have different coefficient of thermal expansion (CTE, $\Delta_{CTE} = 4.10^{-6}$), hence large shear stresses develop in the bond when temperature changes. The stress grows very large, due to the singularity at the free edge of the bond. The bonding is solicited with temperatures changes of several hundreds of degrees firstly during the manufacturing step, then during the operation life. The tile bonding joint must withstand stresses close to or beyond the yield strength. (2) The phase diagram contains brittle intermetallic and intermediate metastable phases [3].

There is currently no significant industrial application with beryllium to copper bonding for commercial application. The industrial experience is mainly the one built from bonding R&D which has been on-going using small scale mock-ups since more than 20 years in various fusion organisations and laboratories around the world [4–7]. Investigated topics include:

- Manufacturing processes (bonding technique, heat/pressure cycles).
- Geometrical effects (tile size, flat or curved bond, local geometry at the bond extremity).
- Material effects (base material grades).
- Intermediate layer or coating, pre assembly cleaning processes.
- Effect of fast surface transient heat load and irradiation on bond properties.

This extensive R&D phase allowed to build a large knowledge basis for the behaviour of the Be/Cu bond, albeit for different base materials, tile sizes, or bonding processes. With the approach of the manufacturing phase, the R&D activity is diminishing (although some aspects are still being investigated as described later in this paper) and the focus is set on the qualification stage (Fig. 2) in preparation for the manufacture. Two bonding techniques are finally selected for joining the tiles of the ITER first wall: brazing and hot isostatic pressing [8,9]. For these two processes, many parameters affect the bond quality. Some of them are still quite sensitive to precise manufacturing conditions, which makes them critical manufacturing steps. Part of the monitoring relies on a qualification process.

Before full scale qualification, an intermediate qualification step is defined. This qualification (sometimes called "pre-qualification") is explicitly planned by the ITER agreement for critical components being manufactured by multiple DAs. For the first wall programme, this step aims at validating the tile bonding process selected by the DA and contributing to stabilise the data obtained during the R&D phase. It focuses the component development effort towards a limited number of series relevant manufacturing processes. The complete qualification occurs at the stage of the full scale prototypes (FSP), and has also the objective of validating the manufacturing lines by the industrial suppliers. This final qualification is not developed here.

The pre-qualification programme is based on small scale mock-ups, and a defined semi-prototype design (SP). Both small scale mock-ups and the SP are to be tested under relevant heat load for a significant number of heat cycles.

(1) The qualification component (the SP) needs to demonstrate adequate bonding of a representative set of plasma facing unit/tiles of the final design (tile size, facets, significant number of tiles, several fingers, cooling circuit). The design of the SP is about 1/6 of the FW panel size, representing 6 plasma facing units, 3 facets, 80–1000 tiles depending on the tile size. The cooling circuit and finger cross-section are representative of the FW panel design. However, it is admitted that the supporting structure and component water connection might differ from the panel design. These are not critical features of the FW panel design, and are to be qualified at the FSP stage.

(2) The testing includes both factory tests (helium leak testing, water flow test, pressure test, UT) and high heat flux testing. The heat flux testing has to be done on a qualified heat flux test bed, which has already demonstrated the capability to testing similar components under similar testing protocols. The testing programme encompasses the criteria of the 'design by experiment' rules (Table 1). The success criteria are that no failure shall occur during the testing, as well as no detachment of any beryllium tile and no loss of beryllium material. There are also quantitative criteria based on the surface temperature of the beryllium tiles, namely no variation of the maximum surface temperature exceeding 20% (measured in °C) during the test, and no "hot spots" (location where temperature is higher than 30% (measured in °C) when compared to surrounding area). The success criteria are a compromise between setting a high standard for bond success, while ensuring that heat flux test can be achieved within acceptable time and resources. This is the reason for the step 2 testing at 125% the design heat load, which aims at doing accelerated fatigue. The heat load of 125% the design heat load is selected so that there is still an acceptable margin to critical heat flux. The success criteria are also backed by

Table 1
Criteria for SP qualification.

Testing step	Number of test cycles	Surface to be tested (%)
NHF – design heat load 2 MW/m²		
2 MW/m²	7500	50
2.5 MW/m²	1500	5
EHF – design heat load 4.7 MW/m²		
4.7 MW/m²	7500	50
5.9 MW/m²	1500	5