Analysis of a tile repair technique based on brazing process for ITER First Wall

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1. Introduction

1.1. Context

The ITER First Wall (FW) component, part of the ITER Blanket system, is a key plasma facing component. It has to provide two of the key Blanket functions: cooling to accommodate high heat loads (heat flux, neutron heating and electromagnetic loads); and an adequate boundary with the plasma while minimizing the contamination impact (low influx of impurities to the plasma) [1,2].

In order to achieve its required functionalities, the FW design includes plasma-facing units disposed on ‘fingers’ toroidally orientated. These fingers, 0.5–0.9 m long, are designed following two different technologies optimized for accommodating the different levels of heat loads: ‘Normal Heat Flux’ (NHF) technology, capable of accommodating 2 MW/m²; and an ‘Enhanced Heat Flux’ (EHF) technology capable of accommodating 4.7 MW/m² [1]. Three procuring agencies are responsible for the design details and manufacturing routes based on their industrial knowhow and capability: NHF by Europe; and EHF by Russia and China. The work here presented is focused on NHF technology in collaboration with ‘Fusion for Energy’ (F4E –European Domestic Agency).

Each NHF finger consists of (see Fig. 1 and [1]): 316L(N)-IG austenitic steel cooled support structure (providing a return water circuit

Abbreviations: Be, Beryllium; Cu, Pure Cooper; CuCrZr, Copper Chromium Zirconium; EHF, Enhanced Heat Flux (first wall); EU, European Union (domestic agency); FE, Finite Element; FW, First Wall; HIP, High Isostatic Pressure (manufacturing technique); HTC, Heat Transfer Coefficient; NHF, Normal Heat Flux (first wall); PFC, Plasma Facing Component; RF, Russian Federation (domestic agency); UT, Ultrasonic Test
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and cooling for nuclear heating), a heat sink made of steel pipes (316L (N)-IG) and copper chromium zirconium alloy (CuCrZr); and beryllium tiles working as armour material bonded to the CuCrZr base with a copper interlayer of two millimetres. HIP manufacturing technique is chosen for bonding the multi-material structure together, with the bonds established from the Be tile to the Cu interlayer and in turn to the CuCrZr base being of critical importance to the successful performance of the panel. More information concerning NHF design and manufacturing may be found in [3–5].

1.2. Motivation and proposed repair technique

The reliability of the plasma facing components (PFCs) is essential for proper operation of a fusion machine. The PFC operation strongly depends on the quality of the bond between the armour tiles facing the plasma and the heat sink material. Different thermal expansions of the bonded materials cause a stress distribution in the bond, which peaks at the bond edge.

Once the FW component is manufactured, it is necessary to perform quality checks that will definitely confirm its acceptability following the specifications. More precisely, failures of the bond to the beryllium tile might occur during the fabrication and under high heat flux qualification. If an unacceptable defect is detected on the tile bond [2], an action has to be taken.

One particularly promising technique consists of a total replacement of the tile, which would be joined again with a brazing process specifically designed for this purpose (Fig. 2). A proper replacement and repair of the tile implies a final good quality of the new bond without damaging the rest of the component. This means that the repairing brazing process has to: avoid degradation on CuCrZr base material, limit the surface beryllium tile temperature, limit the temperature and heat exposure to the neighbouring tiles, etc. Moreover, the brazing material shall be compatible with other possible constraints or requirements as part of the ITER PFCs: impurities going to the plasma, vacuum compatibility, low activation, etc.

References [6–9] propose different repair techniques for different PFC concepts designed for working at high temperatures at the bond region. As a consequence, it is seen that high temperature brazing might be an applicable technique for the repair of the EHF First Wall with Be tiles and the ITER Divertor with W tiles. However, EHF and NHF have crucial differences on both, design and manufacturing methods: the EHF Be/CuCrZr bond relies on high temperature brazing without an interlayer; whereas the NHF Be/CuCrZr bond relies on HIP and a Cu interlayer (as previously presented in 1.1 and Fig. 1).

Due to those key differences, the repair method for the EHF FW (high temperature brazing) is not necessarily the most convenient for the NHF FW. By contrast in the case of NHF, a low temperature brazing method with gold alloy as brazing material and an electron beam gun as heating source is proposed.

The complexity of this latter method motivates the engineering analysis presented in this paper in order to better understand its feasibility. Two different approaches based on thermal assessment are suggested: first, a steady-state thermal analysis explores possible thermo-hydraulic conditions (via the pre-existing cooling channels) as well as the influence of the thermal contact conductance on the thermal behaviour of the component; secondly, a thermal transient analysis allows reproduction of the brazing process in detail, providing insight into the temporal evolution of the component.

2. Parameters involved on the brazing process

The brazing process has to be designed taking into account that the component might suffer some damage due to high temperatures on materials and/or neighbouring tiles. Trying to avoid adding damage to the component, several parameters are selected as particularly relevant for designing the right repair brazing process: heat load; fluid conditions; thermal contact conductance at the interface while establishing the new bond; and finally, the braze temperature (temperature at the bond during the brazing process).

Considering the main parameters presented above, it may be concluded that designing a brazing technique mainly requires: defining heat and cooling conditions (for each step of the process); choosing the right braze material (with the required melting point); controlling the temperature at the heat sink avoiding adding damage on it and the surrounding tiles.

Each is discussed in the next subsections.

2.1. Heat load and coolant conditions

Depending on the brazing process requirements, different heat sources may be considered. The easiest would be heating the entire component in an oven or just keeping a fluid flowing through the channels at the required bonding temperature (and waiting sufficiently for the component to achieve a steady-state condition with uniform temperature).

However, as will be presented in greater detail in subsection 2.5, the heat sink material may require a non-homogeneous heat distribution on the component in order to allow the required elevated bond temperature to be achieved locally while the remainder of the component is maintained at lower temperatures. This kind of process would require a combination of heat applied to the bond, with simultaneous cooling provided by a coolant flowing with appropriate velocity and...
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