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Development of the armoring technique for ITER Divertor Dome

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ABSTRACT

This paper describes the current status of the technique for armoring of Plasma Facing Units (PFUs) of the ITER Divertor Dome with flat tungsten tiles planned for application at the procurement stage.

Application of high-temperature vacuum brazing for armoring of High Heat Flux (HHF) plasma facing components was traditionally developed at the Efremov Institute and successfully tried out at the ITER R&D stage by manufacturing and HHF testing of a number of W- and Be-armored mock-ups [1,2]. Nevertheless, the so-called "fast brazing" technique successfully applied in the past was abandoned at the stage of manufacturing of the Dome Qualification Prototypes (Dome QPs), as it failed to retain the mechanical properties of CuCrZr heat sink of the substrate. Another problem was a substantially increased number of armoring tiles brazed onto one substrate. Severe ITER requirements for the joints quality have forced us to refuse from production of W/Cu joints by brazing in favor of casting.

These modifications have allowed us to produce ITER Divertor Dome QPs with high-quality tungsten armor, which then passed successfully the HHF testing. Further preparation to the procurement stage is in progress.

1. Introduction

D.V. Efremov Institute has been working on ITER since 1988, when this project was established. Development of plasma facing High Heat Flux (HHF) components is one of several fields of Institute activity related to this project. The Efremov Institute has now a procurement contract for ITER Divertor Dome.

The Dome comprises three plasma facing components, i.e. the so called Umbrella, Inner and Outer Particle Reflecting Panels. Maximal heat load is specified as 5 MW/m^2. All these components are formed by annular batches of corresponding Plasma Facing Units (PFUs, see Fig. 1) located on supporting structures fixed to 54 cassette bodies of the Divertor.

ITER Divertor Dome is armored by 8 mm thick flat tungsten tiles joined to the CuCrZr/SS substrates via 2 mm thick ductile layer of OFHC copper. The tile size varies due to toroidal factor, but on average it may be estimated as ~24 mm × 22 mm. The total number of armoring tiles in the Dome is about 73,500. Almost flat configuration of the armor/heat sink interface is suitable for production of these joints by vacuum brazing.

2. Development of new brazing cycle

Application of the so-called "fast brazing" technique, implying use of rather steep warming pulses providing the armor brazing in 10–20 min, was the main principle of the PFU armoring technique developed at the Efremov Institute at the ITER R&D stage. Thermocycling of PFU mockups brazed by this way demonstrated sufficient and even perfect workability of this armoring technique [3].

When preparation for the ITER procurement stage started, the Efremov Institute was nominated for production of Dome Divertor Prototypes (Dome QPs). While the R&D mock-ups were intended mainly for demonstration of the ability to withstand maximum heat fluxes, at the qualification stage the quality and inspection standards became also critical. Particularly, mechanical properties of the CuCrZr heat sink in fabricated PFUs must be kept in a rigorous range.

It is well known that CuCrZr bronze heated above 450 °C loses its mechanical strength, and this degradation progresses with an increase in the exposure temperature and time. Therefore, heating of the CuCrZr/SS substrate up to 810 °C, which is necessary for armor brazing by well-proved STEMET® 108 filler $Cu_{base}Sn_{12}In_7Ni_3$, wt.% [3,4], will invoke some reduction of CuCrZr strength. So first of all, we had to define minimal heating/cooling rates of the brazing cycle retaining acceptable CuCrZr strength.

Such experiment was preformed with series of rectangular ~2 cm × 3 cm specimens cut out from the same 9 mm CuCrZr rolled plate used for manufacturing of the QPs heat sinks. As-received UTS of the plate was about 515 MPa, the chemical composition was

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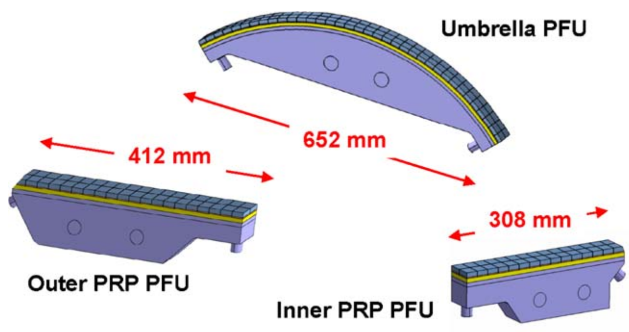

Fig. 1. PFUs of ITER Divertor Dome.

entirely within ITER specifications. The specimens were heated by electron beam up to 810 °C with different rates, kept at this temperature during 30 s for imitation of brazing soaking and then cooled down by heat bridging to the cooled holder. Exposures above 450 °C were from 500 s to 1350 s. Posterior tensile testing of the probes taken from all specimens revealed only the shortest thermal cycle with ∼500 s exposure above 450 °C retains UTS of CuCrZr within a specified minimum of 280 MPa at 20 °C. As far as such fast heating and cooling of rather massive QP, and all the more so, of full-scale Dome PFUs in a conventional vacuum furnace is problematic, application of "fast brazing" technique for armoring of the Dome was cancelled.

To solve the problem it was decided to subject the CuCrZr heat sink to post-brazing strength recovery using a standard cycle of heat treatment, with the brazing being integrated into CuCrZr solution annealing.

Then, the only thing to do was to minimize as much as possible the "extreme" factors of CuCrZr treatment, i.e. to minimize the temperature and time of the solution annealing (as only half a minute at 810 °C is enough for the armor brazing by STEMET® 1108) and to find minimal allowable quenching rate of CuCrZr in order to avoid unnecessary stresses in formed brazed joints during filler solidification.

All these parameters were also optimized in series of experiments with CuCrZr specimens. The defined parameters and idealized profile of the combined thermal cycle are given in Fig. 2.

After successful testing of this combined cycle in several small-scale mock-ups it was applied for armoring of all six PFUs for both Dome QPs. Tensile probes taken from the heat sinks of the mockups

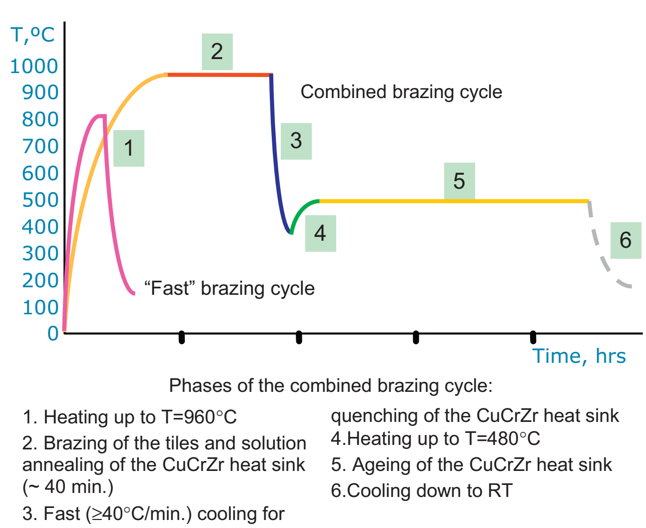

Fig. 2. Phases and idealized profile of the combined armor brazing/CuCrZr treatment thermal cycle.

Table 1
Results of the post-mortem mechanical testing of the QP 1 CuCrZr heat sinks.

PFU No.	T°_{test}, °C	YS, MPa	YS0.2, MPa	US, MPa	UE, %	TE, %
1	20	204	220	353	13.4	18.6
2	20	201	214	331	17.0	24.8
3	20	199	215	339	17.3	22.4
1	250	179	192	279	12.9	20.8
2	250	190	202	274	11.9	21.3
3	250	192	204	271	12.4	21.4

and QP PFUs revealed that CuCrZr properties are within the ITER requirements everywhere. Table 1 lists, as an example, the data on post-mortem tensile test of the probes taken after successful completion of the HHF testing from all three heat sinks of Dome QP No.1.

3. Production of the armor

As mentioned above, the tungsten armor of the Dome is attached to the CuCrZr heat sinks via 2 mm ductile layer of OFHC copper intended to damp the CTE conflict between these materials. At the R&D stage two technological schemes were developed, these are the simultaneous "sandwich" brazing of tiles to the heat sink via a copper sheet interlayer and the brazing of previously manufactured bimetallic W/Cu tiles (Fig. 3). Both techniques demonstrated sufficient reliability of armor joining [4].

Certainly, application of "sandwich" brazing is potentially much cheaper and, at first, this armoring scheme was supposed for Dome PFUs procurement stage. Three small scale "demonstration" Dome mock-ups manufactured and armored by this scheme prior to Dome QPs production withstood thermocycling at a specific heat load up to 8–9 MW/m^2. Nevertheless, ultrasonic examination of these and other additionally made mock-ups constantly revealed presence of brazing defects in the W/Cu joint. Even though these defects were mostly not large and, probably, not so dangerous for the armor attachment reliability (as confirmed by the HHF testing), many defects exceeded limitations specified by ITER. Taking into account considerable number of tiles in one Dome PFU, a lot of Dome PFUs just statistically would be brazed with impermissible defects in the W/Cu joint. At the same time, the CuCrZr joint was always qualitative and gave no rise to concern.

To solve the problem we decided to make the W/Cu joint only by casting and to armor the QPs and serial Dome PFUs using only bimetallic W/Cu tiles. In addition, this option makes possible preliminary examination of the W/Cu joint in the W/Cu plates workpieces for manufacturing of bimetallic tiles.

Casting of copper onto tungsten plates was performed in graphite crucibles in a vacuum resistive furnace allowing directional crystallization of the copper melt. The route of W/Cu tiles production is illustrated in Fig. 4.

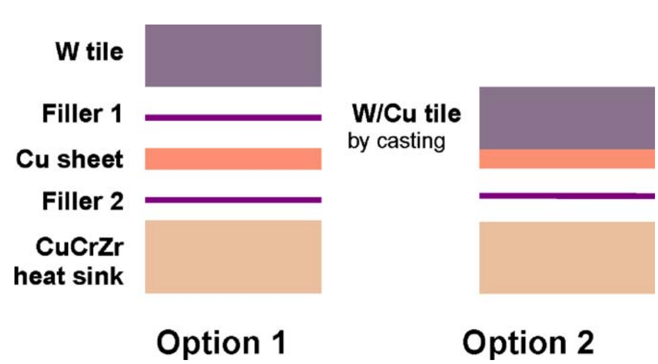

Fig. 3. Two schemes of armoring by brazing.