Fusion Engineering and Design xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

Progress of ITER full tungsten divertor technology qualification in Japan: Manufacturing full-scale plasma-facing unit prototypes

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HIGHLIGHTS

- JADA has demonstrated the feasibility of manufacturing the full-W plasma-facing units (W-PFU).
- The surface profiles of the W monoblocks of the W-PFU prototypes on the test frame to mimic the support structure of the ITER OVT were examined by using an optical three-dimensional measurement system. The results show the most W monoblock surface in the target part locates within + 0.25 mm from the CAD data.
- The strict profile control with the profile tolerance of ±0.3 mm is imposed on the OVT to prevent the leading edges of the W monoblocks from over-heating.
- The present full-scale prototyping demonstrates to satisfy this requirement on the surface profile.
- It can be concluded that the technical maturities of JADA and its suppliers are as high as to start series manufacturing the ITER divertor components.

ARTICLE INFO

Article history:
Received 31 August 2015
Received in revised form
17 December 2015
Accepted 20 December 2015
Available online xxx

Keywords:
Plasma-facing components
High heat flux
ITER
Divertor
Tungsten
Full-scale prototype

ABSTRACT

Japan Atomic Energy Agency (JAEA) is in progress for technology demonstration toward Full-tungsten (W) ITER divertor outer vertical target (OVT), especially, W monoblock technology that needs to withstand the repetitive heat load as high as 20 MW/m^2 for 10 s. Under the framework of the W divertor qualification program developed ITER organization, JAEA as Japanese Domestic Agency (JADA) manufactured seven full-scale plasma-facing unit (PFU) prototypes with the Japanese industries. Four prototypes that have 146 W monoblock joint with casted copper (Cu) interlayer passed successfully the ultrasonic testing. In the other three prototypes that have the different W/Cu interlayer joint, joint defects were found. The dimension measurements reveal the requirements of the gap between W monoblocks and the surface profile of PFU are feasible.

1. Introduction

Upon recommendation of the ITER council November 2011 to study the possibility of starting operation with a full W armored divertor with the objective to make a decision on the final material by the end of 2013, ITER organization (IO) and Japan Atomic Energy Agency (JAEA) as Japanese Domestic Agency (JADA) are actively working on the development and demonstration on the full-W divertor concept under the framework of the task agreement of ITER full tungsten divertor qualification program [1,2]. JADA is in charge of technology development and demonstration for manufacturing ITER Divertor Outer Vertical Target (OVT, see Fig. 1) together with Japanese industries. In the first phase of this qualification program, IO and JADA have demonstrated the armor heat sink bonding technology and the heat removal capability of W monoblock joint to the Cu-alloy cooling tube against the heat load of 20 MW/m^2 [3]. Based this achievement, IO and JADA have manufactured full-W plasma-facing units (PFU) prototypes for full-scale demonstration. In the present full-scale demonstration, dimensional controls of the PFU prototypes are one of the key challenges as well as sound joints of 146 W monoblocks to a cooling tube because of the strict dimensional requirements onto ITER full-W divertor to protect leading edges of the W monoblocks against the magnetic fieldline [1]. The present study reports the results of manufacturing of the W-PFU

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http://dx.doi.org/10.1016/j.fusengdes.2015.12.049

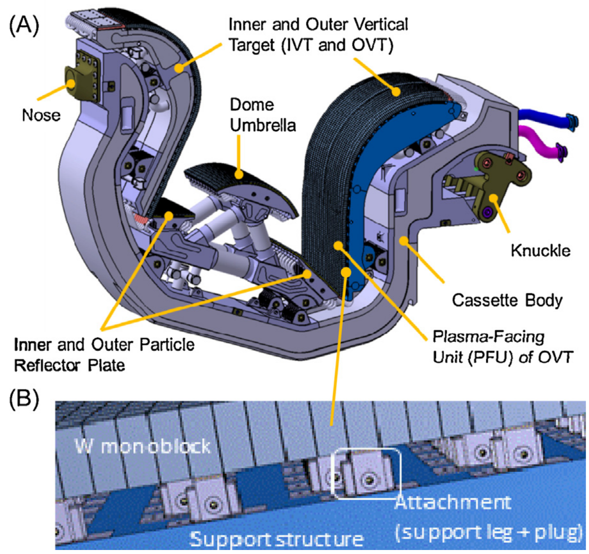

Fig. 1. (A) 3D view of the ITER W divertor and (B) W monoblock attachment to Support structure.

full-scale prototypes and examination, e.g., dimensional controls and non-destructive testing (NDT) results obtained from the prototypes.

2. Full-W divertor qualification program [1,2]

The qualification program developed by IO in early 2012 consists of two steps:

(1) Technology development and validation:
The objective of this step is demonstration of the fitness-for-purpose of the proposed technology by means of manufacturing and HHF testing of small-scale W monoblock mock-ups, and W monoblock attachment joint and testing. This step was completed successfully in early 2014 and reported already.
(2) Full-scale demonstration: technology demonstration via full-scale-prototype manufacturing and HHF testing.
The most demanding requirements in the program is to demonstrate the thermo-mechanical fatigue performance under the design stationary loads (typically 10 s on/10 s off): 5000 cycles at 10 MW/m^2 and 300 cycles at 20 MW/m^2. The activity is in progress among Domestic Agencies (DAs), namely, Japanese and European Das [4] (manufacturing of PFU prototypes) and Russian DA (high heat flux (HHF) testing).

JADA started to manufacture the W-PFU prototypes and prepare the HHF testing on them as reported here.

3. Full-scale demonstration

3.1. Manufacturing full-scale PFU prototypes

JADA have manufactured six plus one additional full-W full-scale PFU prototypes (see Fig. 2) with different two Japanese industries (PFU suppliers). The six prototypes were manufactured according to with the IO's quality assurance program. Each prototype has 56 W monoblocks in the target (straight) part that will receive the highest heat load during the operation and 90 W monoblocks in the baffle part as shown in Fig. 2. These W monoblocks are made out of rolled W plates with the material specification defined by IO [5]. The W monoblocks were jointed to a pure copper (Cu) interlayer with thickness of 1.3 mm. The W

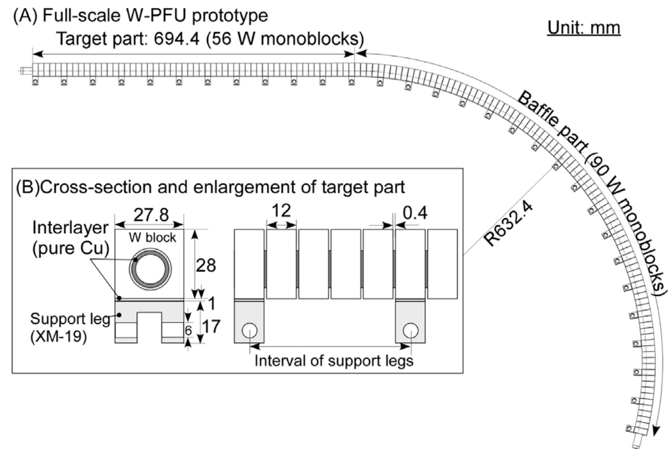

Fig. 2. Schematic drawing of full-scale W-PFU prototype.

monoblocks used in the present study were manufactured by two different W suppliers and JADA supplied them to the PFU suppliers. Typical dimensions of the W monoblock are 27.8 mm in width, 28 mm in height and 12 mm in the cooling tube axial direction for the target part. The distance from the plasma-facing surface of W monoblock to (so-called armor thickness) is 7.7 mm. The surface of the W monoblock for the target (straight) part of the prototype was not chamfered or shaped in the toroidal direction (in the perpendicular to the axis of the cooling tube) that is required for the series production. The joint techniques of the Cu interlayer to the W monoblocks depend on the W suppliers; one is casting and the other is unidirectional diffusion bonding at high temperature. The W/Cu joint interface is examined with an ultrasonic technique by the W suppliers before assembling the prototypes. The cooling tubes are made of CuCrZr-IG and their outer and inner diameters are 15 and 12 mm.

Typical assembling and bonding processes in manufacturing the prototypes are as follows:

1. Transition short tube made of alloy 625 and 316 L is jointed to both the end of the CuCrZr-IG cooling tube with welding and the joints are controlled by non-destructive testing (NDT) such as radiographic testing (RT) and dye penetrant testing (PT).
2. Bonding the XM-19 steel blocks to the W monoblock with pure-Cu interlayer was followed by ultrasonic testing (UT) for the bonding interface. Bonding was done by hot-isostatic pressing or brazing. After acceptance of UT, the XM-19 steel blocks are machined to the final geometry of the support leg as shown in Figs. 1 and 2.
3. The W monoblocks with the Cu interlayer are fit onto the CuCrZr cooling tube with brazing filler to bond the Cu interlayers to the cooling tube. The brazing filler is Ni-Cu-Mn alloy. The axial gaps between the W monoblocks are set to the specific values with the insertion of the spacers. These values after heat treatments are measured and the results are shown in the later section.
4. The baffle (curved) part of the cooling tube is bent with dedicated jigs to a specific radius.
5. The prototypes are mounted for brazing and heat treatments in the vacuum furnace. The brazing (solution annealing) temperature is set at 980 °C followed by gas quenching and by aging heat treatment at 480 °C to recover the mechanical properties of the CuCrZr cooling tube. The target value of cooling rate after holding at the brazing temperature is around 1 °C/s to achieve both sound joints of W/Cu and Cu/CuCrZr interface, and the recovery of mechanical properties of the CuCrZr cooling tube. Test samples of the CuCrZr tube are simultaneously processed

Please cite this article in press as: K. Ezato, et al., Progress of ITER full tungsten divertor technology qualification in Japan: Manufacturing full-scale plasma-facing unit prototypes, Fusion Eng. Des. (2015), http://dx.doi.org/10.1016/j.fusengdes.2015.12.049