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A study of plasma facing tungsten components with electrical discharge machined surface exposed to cyclic thermal loads

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ABSTRACT

Through R&D for a plasma facing units (PFUs) in an outer vertical target of an ITER full-tungsten (W) divertor, Japan Atomic Energy Agency succeeded in demonstrating the durability of the W divertor shaped by an electrical discharge machining (EDM). To prevent melting of W armors in the PFUs, an adequate technology to meet requirements of a geometrical shape and a tolerance is one of the most important key issues in a manufacturing process. From the necessity, the EDM has been evaluated to control the final shape of the W armor. Though the EDM was known to be advantages such as an easy workability, a potential disadvantage of presence of micro-cracks on the W surface appeared. In order to examine a potential effect of the micro-crack on a heat removal durability, a high heat flux testing was carried out for the W divertor mock-up with the polish and the EDM. As the result, all of the W armors endured the repetitive heat load of 1000 cycles at an absorbed heat flux of more than 20 MW/m^2, which strongly encourages the realization of the PFUs of the ITER full-W divertor with the various geometrical shape and the high accuracy tolerance.

1. Introduction

In the autumn of 2011, the ITER Organization (IO) proposed to start with the full-tungsten (W) divertor target as the first divertor throughout all phases including the nuclear operation because of a cost containment by reduction of the replacement of the ITER divertor. In the November of 2011 [1,2], the ITER Council (IC) endorsed recommendation to decide the specific choice of the first divertor within approximately 2 years.

In this moratorium, Japan Atomic Energy Agency (JAEA) as the Japan domestic agency (JADA) performed research and developments (R&Ds) of manufacturing to ensure a technological feasibility for the high heat flux (HHF) components required in the full-W divertor designed by the IO as shown in Fig. 1.

In 2013, as the first step of the technology validation and demonstration of the full-W divertor [3,4], JAEA succeeded in demonstrating the durability of the full-W small-scale mock-ups which endured a repetitive heat load of 5000 cycles at 10 MW/m^2 and 1000 cycles at 20 MW/m^2 [5–7]. This result of the R&D provided one of sufficient elements for an informed decision on the full-W divertor to the IO. After this demonstration, the IC approved the decision of the full-W ITER divertor from initial period in the baseline.

In 2014, as the second step, JAEA manufactured a full-scale prototype of plasma facing units (PFUs) to demonstrate the manufacturing technology [8], and the performance testing is scheduled in 2015. Through the R&D for the full-scale prototype PFUs [5], to meet a geometrical tolerance of neighboring W armors on the plasma facing surface [3] was a challenge. To suppress melting the W armor at leading edge in the plasma operations, an adequate technology to meet the requirements for the geometrical shape of the plasma facing surface is one of the most important key issues in the manufacturing process.

A mechanical polishing or an electrical discharge machining (EDM) or both are supposed to be alternatives for a control the final shape of multiple W armors after the brazing of the PFUs. The mechanical polishing with a cylindrical grinding machine has been employed before the brazing of the PFUs in a manufacturing process of one W armor for the procurement activity by the JADA so far. However, multiple W armors brazed to a pipe have not ever been mechanically polished at a time.

The EDM was known to have advantages such as an easy workability for the control of the final shape. On a potential disadvantage side, the EDM inevitably caused a micro-cracks on the W surface

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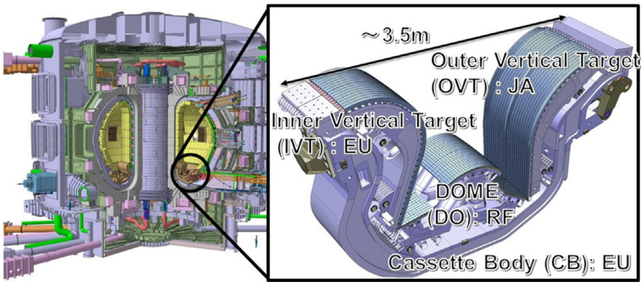


Fig. 1. Configuration of ITER divertor [3].

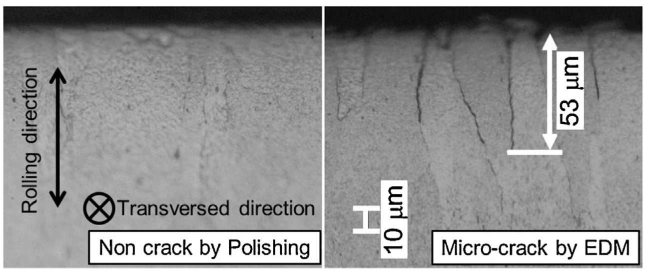


Fig. 2. Cross-sections of W monoblock with polishing and EDM.

[9] as shown in Fig. 2. The micro-crack retains a potential to cause a loss of a heat removal capability if the micro-crack on the surface propagates inside the W armor and breaks the brazing surface. This paper reports on the durability of the micro-crack on the W armor with the EDM against the HHF testing.

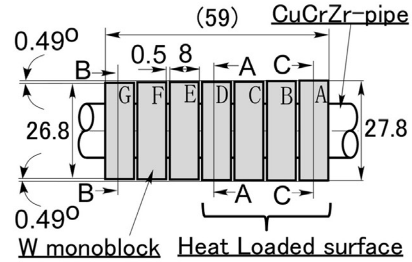
2. Procedures of manufacturing of W divertor mock-up and HHF testing

2.1. Manufacturing process of W divertor mock-up

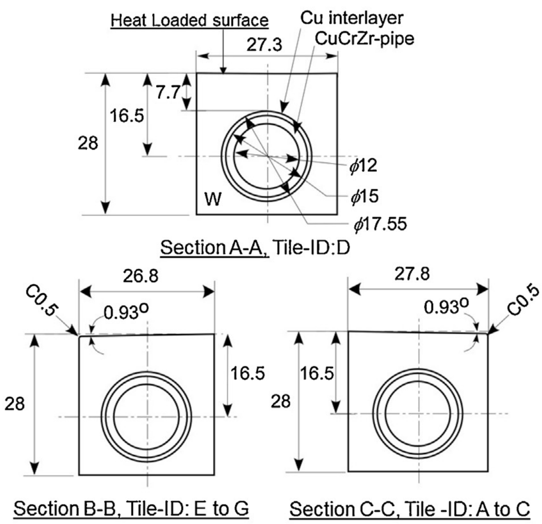
Configuration of W divertor mock-up and its cross-section are shown in Fig. 3a and b, respectively. A simple chamfer in toroidal direction with a scale-height of 0.5 mm (angle of 0.93°) is applied to shadow a leading edge of the monoblock [2]. The W divertor mock-up was manufactured to demonstrate the applicability of the EDM for the control of the final shape of multiple W armors after the brazing.

In a manufacturing process of the W divertor mock-up, a W monoblock to Cu-interlayer joint was of the same importance as a Cu-interlayer to CuCrZr-pipe joint for maintaining the heat removal capability. JAEA performed to improve the bonding method of the W and Cu-interlayer joint [5]. W monoblocks in this mock-up were manufactured by a Chinese company, the Advanced Technology & Materials Co., Ltd. (AT&M). As for the bonding method of the W and Cu-interlayer, a HIP bonding [10] was applied. Additionally, all outside surfaces of W monoblocks were polished with a cylindrical grinding machine to meet the dimension tolerance for the complete cuboidal shape of W monoblock without chamfers. Although thickness of 12 mm was specified in the ITER divertor, the thickness of 8 mm in this mock-up was prepared to confirm a durability of thinner W monoblock for HHF testing.

The Cu-interlayers of seven W monoblocks were brazed on the CuCrZr-pipe by the Kawasaki Heavy Industry, Ltd. (KHI) simultaneously. The brazing temperature for this mock-up was almost same heat treatment [6] for the outer vertical target of the ITER except for a smaller cooling rate than 1 °C/s from an annealing. Until this stage, a three-dimensional geometry of all W monoblocks is the rectangular parallelepiped without chamfers.



(a) Top view from a source of an electron beam gun.



(b) Cross-section of W monoblocks

Fig. 3. W divertor mock-up with polishing and EDM.

2.2. Non-destructive examination

Key point of the quality control of the PFUs is to ensure a soundness of the bonding interfaces. In the manufacturing process, the UT (pulsed echo method) applied as a non-destructive examination to check the soundness of all the armor and heat sink joints, i.e., the W/Cu-interlayer and the Cu-interlayer/CuCrZr as shown in Fig. 3b. The W divertor mock-ups prior to the EDM passed the UT after the brazing process.

2.3. Shaping process on plasma facing surface

The final shape of the plasma facing surface by the EDM aims at the realization of the PFUs near a strike point as seen in Fig. 4. Seven W monoblocks are identified by alphabetical characters in Fig. 3a. The EDM was performed by a Japanese company, A.L.M.T. Corp. (ALMT) to the plasma facing surface and two lateral surfaces after the brazing.

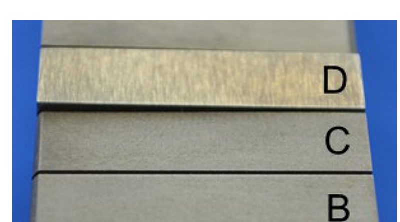


Fig. 4. Final shape of the plasma facing surface.

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