Progress of Manufacturing and Quality Testing of
the ITER Divertor Outer Vertical Target in Japan

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Abstract. The outer vertical targets of the ITER divertor are procured by the Japan Domestic Agency, JADA. Manufacturing a full-scale prototype of the half cassette which consists of 11 plasma facing units and a steel support structure has been started in Japan. JADA has greatly improved the success rate of the joint between the plasma-facing materials and heat-sink materials, in consequence of R&D on joint technology and quality control. JADA solved problems of quality control of the joint interface by an improved system of infrared thermography inspection, which provides quick feedback during the manufacturing process about the presence of defect in the joint. This paper reports on the achievements and the clarifications of technical and quality issues for the manufacture of the divertor components to be supplied by Japan.

1. Introduction

Japan Domestic Agency (JADA) has started manufacturing 11 plasma facing units (PFUs) of a full-scale prototype as shown in FIG. 1 which is just the same as those of a half cassette of an outer vertical target (OVT) in the ITER divertor [1]. This PFU, which is based on the present design proposed by the ITER organization (IO), consists of carbon fiber composite (CFC) monoblocks, tungsten (W) monoblocks and CuCrZr tubes. At the beginning of this activity, a joint technology and quality control for an interface between plasma-facing material and heat-sink material were key issues in the manufacturing process of the PFUs. In consequence of research and development, JADA achieved to increasing the success rate of the joint by improvements which are to metalize the joint surface of the CFC by the use of Ti-coating with accurate thickness controlling, and also to change buffer layer material from soft copper to tungsten-copper (W/Cu) alloy. Moreover, JADA solved the problems of the quality control of joint interface by improved a system of an infrared thermography inspection which provides quick feedback to the manufacturing process about the presence of defect in the joint. Before manufacturing the PFUs of the full-scale prototype as shown in FIG. 1, a pre-prototype of PFU was manufactured as a final exercise toward the manufacturing. The result from the infrared thermography inspection indicates a good joint quality. Based on the result from manufacturing the pre-prototype of PFU, the first 6 PFUs for the prototype were manufactured at the end of June 2011. The manufacturing of the rest is scheduled in 2013. In parallel to above development, R&D of the W monoblocks enough to endure the repetitive heat load of more than 20 MW/m² has been started to support the design activity underway in examination of the possibility to select a full-W PFU without CFC in the IO until autumn.
2013. JADA performed the high heat flux testing of two mock-ups in which Cu and W are jointed by using a non defect bonding. The purpose is to demonstrate that the soundness of the non defect bonding is sufficient against the repetitive heat flux of 20 MW/m² for 1,000 cycles except for the recrystallization of W. This paper presents the overview of achievements and clarifications of technical and quality issues for the manufacturing activity and the quality control of the divertor in Japan.

2. Material selection and procedure for Quality of jointing

JADA adopted the joint technology between the CFC monoblocks, a CuCrZr tube and the buffer layer based on a brazing condition in high temperature with noble-metal-free filler. Though Ti-Cu-Ni alloy was directly inserted between them as a brazing filler metal, a lot of joint defects took place in the past experience [2]. The reasons of the joint defect were a lack of wettability of the brazing filler and a break of CFC monoblock caused by a deformation of the CuCrZr tube during a heat treatment process of the brazing and an aging. To improve wettability, Ti-coating is applied to metalize the CFC joint surface. And its thickness is strictly controlled because the gap between the CFC monoblock and the buffer layer is a key parameter for the high temperature brazing. On the other hands, candidate material as the buffer layer is the W/Cu alloy instead of the soft copper. The interlayer collar of the W/Cu was sandwiched in between the CuCrZr tube and the CFC with braze fillers of Ni-Cu-Mn (NiCuMn37) as shown in FIG. 2. The W/Cu has intermediate value of thermal expansion coefficient between the CFC monoblock and the CuCrZr tube, and higher mechanical strength than Cu. It is adapted to decrease a deformation amount of CFC monoblock caused by deformation of the CuCrZr tube in the heat treatment processes. JADA demonstrated that the three mock-ups fabricated by using the joining process withstood the repetitive heat load of more than 20 MW/m² for 1000 cycles [3] before the manufacturing of the OVT full-scale prototype.

3. IR inspection for quality control of jointing plasma-facing material to heat-sink material

One of the key points of the manufacturing of the PFUs is the quality control at the joint interface especially the armor tiles of the CFC. In the manufacturing process, an infrared thermography method [4-6] is mainly applied for the inspection of the joint defect for the CFC part. A facility of the infrared non-destructive examination for divertor called “FIND” has been installed in Japan Atomic Energy Agency (JAEA) for R&D on the inspection technique for the divertor of ITER and JT-60SA as shown in FIG. 3(a). Two mirrors made of stainless steel are mounted at a side of each channel in FIND, which is different from the SATIR[4]. Therefore, the temperature on three surfaces of the CFC monoblock is able to be simultaneously observed by this JADA’s peculiar way.

3.1. Facility and procedure of infrared non-destructive examination for divertor

FIG. 3(b) shows the diagram of the FIND including circulation loops of hot and cold water. The hot and cold water are prepared as to be specified temperature and reserved in each tank
which has a capacity of 2 m$^3$. The pipes mounted in FIND are beforehand heated and cooled by circulation of the hot and cold water, respectively, so as to be the predefined temperatures. The circulated water keeps stable temperature during the inspection. The heater and the chiller capabilities for the hot and cold water are 60 kW and 15 kW, respectively.

Three turbine flow meters are installed into each channel as shown in FIGS. 3 (a) and (b). The accuracy of the flow meter is ± 0.5% of full scale within the range of the flow rate between 0 L/min and 200 L/min.

The capabilities of pumps for the hot and cold water are 15 kW of output, 150 m of total head at 360 L/min, discharge pressures of 1.8 MPa at 306 L/min and 1.5 MPa at 360 L/min. Maximum value of transient pressure in inlet header is around 2.0 MPa in both cases of 102 L/min and 120 L/min in each channel of test section. In the case of small pressure drop in the pipe of small-scale test sample and in a flexible tube etc., the flow rate will be set to be 120 L/min. On the other hand, in the case of large pressure drop, that is caused by a large scale mockups or full-scale PFU, the flow rate of 102 L/min will be applied. In this paper, the results at flow rate of 102 L/min are described.

![Photograph of the FIND](image1)

(a) Photograph of the FIND.

![Diagram of the FIND](image2)

(b) Diagram of the FIND

FIG. 3. The facility of infrared NDE for divertor (FIND) in JAEA.
The CFC monoblock heated at 95 °C by the hot water in steady state condition is instantaneously cooled down by the cold water flow of 5 °C in the channels. The temperatures of the hot and cold water are measured by thermocouples at the inlet pipes illustrated in FIG. 3(b). The accuracy of thermocouple, which is Type T, 1.6 mm of diameter sheath and a grounded type of measuring junction, is ± 1.0 °C.

Fast action of switching from the hot water to the cold water is performed by air-pressure-operated valves as shown in FIG. 3(b). The valves are installed at downstream of the inlet header and at upstream of the outlet one to rapidly switch from the hot water to the cold water. The hot water which remains in pipes can be purged by the cold water.

Transient thermal responses on the tested surfaces are monitored and recorded with an infrared camera (IR camera) for more than 7 seconds. The IR camera is ThermaCAM SC640 / FLIR of which resolution is 640×480 pixels. The accuracy of IR camera is ± 2 °C of reading within the temperature range between -40 °C and +100 °C. The sampling frequency is 30 Hz and scanning mode is non-interlaced.

After the thermal transient, the thermographic inspection is performed via calculation of the maximum temperature difference between the defect-free CFC monoblock and the test object. In this operation, FIND is able to detect the integrated defects in the CFC monoblock and its joint interface.

### 3.2. Calibration CFC monoblock and analysis for temperature difference

In this inspection, it is of importance to predict various sizes of defects at the joint interfaces from a different transient thermal response obtained by the IR image. Therefore, JADA has performed a construction of a database for a correlation between a known defect and its transient thermal response. The mock-ups with an artificial defect as shown in FIG. 4(a), which consists of only one CFC monoblock, were manufactured for establishment of the database. The Geometry, dimensions and materials of the CFC monoblock for the calibration of temperature differences correspond exactly to that shown in FIG. 2. However, the twisted tape is not inserted under the thermographic inspection. These mock-ups have the artificial defects inside the CFC of joint line obtained by electric-discharge machining (EDM) as shown in FIG. 4(a) after the joining of the CFC monoblock onto the pipe. FIG. 4(b) shows the explanation diagram for definition of defect in calibration monoblock. In this figure, an angle degree of Θ indicates a circumferential position. That of ΔΘ indicates maximum perimeter of the defect.

![FIG. 4. (a) Artificial defects inside the CFC of joint line obtained by the EDM. (b) Diagram for definition of defects in calibration monoblock. Angle degree of Θ indicates a circumferential position. That of ΔΘ indicates maximum perimeter of the defect.](image)
Location $\Theta = 0^\circ$, size $\Delta \theta = 40, 50, 60, 70^\circ$ and location $\Theta = 45^\circ$, size $\Delta \theta = 40, 50, 60, 70^\circ$.

Two mock-ups with each defect of 30 and 40 degrees were also added above the mock-ups. In addition to the mock-ups with the defects, three reference mock-ups with a sound joint of CFC and Cu were prepared.

3.3. Analysis of IR image

Fig. 5. (a) Relationship between the view of IR camera and that of IR image for the surfaces of a monoblock. (b) Definition of $DT_{\text{ref}}$ detective angle degree of a circumferential position.

Fig. 6. Contours of temperature differences between CFC monoblock with artificial defect and one with defect-free at 102 L/min of flow rate. Red collar shows the 10 degrees of maximum temperature difference, and blue one shows the zero in the legend of collar contour.

The transient thermal response of the tested surface is monitored and recorded with the IR camera. The two mirrors are installed to measure three surfaces of the sample at a time. One surface captures the real image to inspect the plasma facing wall. The others capture the images of the mirrors to inspect the two sides of the monoblock as shown in Fig. 5(a). Here, the left and right sides of monoblock from outlet of test section are defined. The artificial defect in each CFC monoblock is located at left side in all of the examinations. It also contributes to reducing a time cost of inspection. A temperature difference, $DT_{\text{ref}}$, in each pixel of a surface is expressed as follows;
$DT_{\text{ref}} = \max |T - T_{\text{ref}}|.$ \hfill (1)

Here, $T_{\text{ref}}$ indicates the surface temperature of reference which is defect-free of CFC monoblock. The surface temperature of the test sample of CFC monoblock with an artificial defect is expressed as $T$ in Eq. 1. The maximum value of difference between $T_{\text{ref}}$ and $T$ during whole transient time in a surface is expressed as $DT_{\text{ref}}$. The position of maximum $DT_{\text{ref}}$ in each surface is also detected and shown in results as $DT_{\text{ref}}$ detective angle degree of a circumferential position as seen in FIG. 5(b).

FIG. 6 shows contours of temperature differences at each pixel between CFC monoblock with artificial defect and one with defect-free. The defect can be visually detected by expression of temperature differences as a three-dimensional configuration. This expression is achieved by a use of the simultaneous observation system in FIND and contributes to quickly supplying the qualitative results of inspection to manufacturing line.

### 3.4. Experimental correspondence between DTref, the defect size and location

The averaged $DT_{\text{ref}}$ for experimental correspondence between $DT_{\text{ref}}$, the defect size and location for all of the samples at the flow rate of 102 L/min were inspected at FIND. FIGS. 7(a) and (b) show the averaged $DT_{\text{ref}}$ on the plasma facing surface and the side walls against the artificial defect size for $\Theta = 0^\circ$ and $45^\circ$ at 102 L/min. In the case of $\Theta = 0^\circ$, the values of $DT_{\text{ref}}$ increase as square of defect size except for three mock-ups of $\Delta \theta = 40^\circ$ and one of $\Delta \theta = 60^\circ$. In the case of $\Theta = 45^\circ$, the values $DT_{\text{ref}}$ increase with increasing defect size except for each one of $\Delta \theta = 40^\circ$, 50 and 60. Scattering of $DT_{\text{ref}}$ at the same artificial defect size indicates the presence of crack or separating joint-interface except for artificial defect in individual mock-up. There is a possibility that the perimeter of the artificial defect has been extended by a residual stress after EDM. In near future, the monoblock will be cut and be examined to observe a defect in detail.

The detective angles of $DT_{\text{ref}}$ are not shown here, but were also measured in the examinations. In the case of $\Theta = 0^\circ$, the values of detective angles appear near the angle of $0^\circ$. However, in the case of the uniform distribution on the surface temperature such as defect-free, the detective angle scatters.

![FIG. 7. Averaged DTref against artificial defect size at 102 L/min.](image-url)
TABLE I: Criteria expressed as the temperature differences at 102 L/min in FIND.

<table>
<thead>
<tr>
<th>Artificial defect size, Δθ</th>
<th>Position, Θ</th>
<th>Plasma-facing wall</th>
<th>Left side</th>
<th>Right side</th>
</tr>
</thead>
<tbody>
<tr>
<td>50°</td>
<td>0°</td>
<td>8.0</td>
<td>7.2</td>
<td>8.2</td>
</tr>
<tr>
<td>50°</td>
<td>45°</td>
<td>6.7</td>
<td>8.3</td>
<td>4.3</td>
</tr>
</tbody>
</table>

JADA applies the criteria of thermographic inspection described in the procurement arrangement between the IO and JADA. The present criteria are that none of the CFC/Cu joints shall have defects with Δθ > 50°. These values expressed as bolds italics in TABLE I indicate the criteria which are obtained by this experiment at 102 L/min in FIND. JADA keeps applying the criteria of the thermographic inspection until new criteria will be confirmed by a use of data of high heat flux testing.

4. Manufacturing status of OVT full-scale prototype

The pre-prototype of PFU as shown in FIG. 8 was manufactured as a final exercise toward manufacturing the PFUs of the OVT full-scale prototype. The result of the infrared thermography inspection in FIG. 9 indicates a good performance except for a central armour tile. This defect of the central tile was caused by restraint of the extension of the CuCrZr tube-axis direction in the pre-prototype of PFU with brazing jigs during the heat treatment. After this experience, JADA improved the jig to adapt a stretch of CuCrZr tube-axis direction by thermal expansion at the brazing. Based on the result from the OVT pre-prototype of PFU, the first 6 PFUs as shown in FIG. 10 were manufactured until the end of June 2012. High heat flux testing for the 6 PFUs will be started at Russian federation domestic agency from October 2012. Moreover, the manufacturing of the rest 5 PFUs is scheduled in 2013.

**FIG. 8. Appearance of the OVT pre-prototype of PFU.**

**FIG. 9. (a) Contour of decreasing surface temperature and (b) photograph of the OVT pre-prototype of PFU.**

**Fig 10. PFU of the OVT full-scale prototype.**
5. R&D of W monoblocks enough to endure high heat flux (HHF) of 20 MW/m²

In parallel to above development, R&D of the W monoblocks enough to endure the repetitive heat load of more than 20 MW/m² has been started at JAEA electron beam irradiation system (JEBIS)[7]. FIG. 11(a) shows a mock-up with the W monoblocks named "S-TAN" and manufactured by using a non defect bonding (NDB) for the joint between the W monoblock and a buffer layer of Cu which is thickness of 1.2 mm. "S-TAN" which is produced by using HIP process has isotropic microstructure. Two mock-ups were manufactured by a use of "S-TAN". A cyclic thermal loading was set to be 1000 cycles with 20MW/m² which has profile as shown in FIG. 11(b). JADA successfully completed the HHF testing of two mock-ups from the result of keeping a constant decreasing ratio of the temperature from shutdown of the heat flux as shown in FIG. 11(c). The soundness of NDB is sufficient against the repetitive heat flux of 20MW/m² for 1,000 cycles except for the recrystallization of W.

Disclaimer
The views and opinions expressed herein do not necessarily reflect those of the IO.

References