Manufacturing and Development of JT-60SA Vacuum Vessel and Divertor


1Japan Atomic Energy Agency (JAEA), Naka, Ibaraki-ken 311-0193, Japan

E-mail contact of main author: sakasai.akira@jaea.go.jp

Abstract. The JT-60SA vacuum vessel (VV) and divertor are key components for the performance requirements. Therefore the manufacturing and development of VV and divertor are in progress, inclusive of the superconducting magnets. The vacuum vessel has a double wall structure in high rigidity to withstand electromagnetic force at disruption and to keep high toroidal one-turn resistance. In addition, the double wall structure fulfills originally two functions. 1) The remarkable reduction of the nuclear heating in the superconducting magnets is made by boric-acid water circulated in the double wall. 2) The effective baking is enabled by nitrogen gas flow of 200°C in the double wall after draining of water. Three welding types were chosen for the manufacturing of the double wall structure VV to minimize deformation by welding. Divertor cassettes with fully water cooled plasma facing components were designed to realize the JT-60SA lower single null closed divertor. The divertor cassettes in the radio-active VV have been developed to ensure compatibility with remote handling (RH) maintenance in order to allow long pulse high performance discharges with high neutron yield. The manufacturing of divertor cassettes with typical accuracy of ±1 mm has been successfully completed. Brazed CFC (carbon fiber composite) monoblock targets for a divertor target have been manufactured by precise control of tolerances inside CFC blocks. The infrared thermography test of monoblock targets has been developed as new acceptance inspection.

1. Introduction

The JT-60 Super Advanced (JT-60SA) tokamak project [1, 2, 3] has started the construction under both the Japan-EU international program “ITER Broader Approach” and the Japanese domestic program. The vacuum vessel (VV) is a key component of the JT-60SA. The VV has a torus-shaped double-wall structure with stiffening ribs between shells. The main function of the VV is to provide high vacuum for plasma, neutron shielding for nuclear heating reduction on the superconducting magnets and supports for in-vessel components such as divertor cassettes and in-vessel coils for plasma control. The VV manufacturing started in December 2009. The VV is composed of 10 sectors, and three VV 40-degree sectors were completed in May 2012. The manufacturing of each sector is required to be controlled within the tolerance of ±5 mm, because the accuracy of the VV assembly is required to be ±10 mm at the inboard and ±20 mm at the outboard.

Lower single null closed divertor with vertical target will be installed in JT-60SA. Divertor cassettes with fully water cooled plasma facing components and remote handling (RH) system is required to allow long pulse high performance discharges with large neutron yield. The divertor cassettes are to be compatible with limited position and size of maintenance ports. Modularized plasma facing components such as vertical targets, baffles and dome shall be assembled on the divertor cassettes. Manufacturing of brazed CFC (carbon fibre composite) monoblock targets, which can remove 10-15 MW/m² of heat flux continuously at vertical divertor targets, is conducted. Development of acceptance inspection for monoblock targets is also carried out.
2. Manufacturing status of JT-60SA vacuum vessel

2.1. Design of JT-60SA vacuum vessel

The double-wall structure with stiffening ribs between shells was adopted for the JT-60SA vacuum vessel to withstand electromagnetic force at disruption and to keep high toroidal one-turn resistance. Figure 1 shows overall structure of the VV with a D-shaped poloidal cross section and a toroidal configuration of 10-degree segmented facets. Torus outer diameter and height are 9.95 m and 6.63 m, respectively. Inner/outer shells and stiffening ribs of the double wall have 18-mm and 22-mm thicknesses, respectively. The material is 316L stainless steel with low cobalt content (<0.05%) [4, 5]. The VV is composed of 18 port sections with 73 ports for heating system, diagnostics, and cooling pipes of in-vessel components. The design temperatures of T50°C and 200°C, respectively. In the double wall, boric-acid water is circulated at plasma operation to reduce the nuclear heating of the superconducting magnets. For baking, nitrogen gas is circulated in the double wall after draining of the boric-acid water. The circulation unit for the water and the nitrogen gas is 40-degree sector. They flow from the bottom to inboard and outboard separately and flow out of the top of the VV.

The VV is divided into 10 sectors and composed of seven 40-degree, two 30-degree and one 20-degree sectors. A basic manufacturing unit of the VV is a 40-degree sector, which is cut and welded at the position between ports.

2.2. Welding of Double Wall Structure VV

Technical issue for the VV manufacturing is to establish a manufacturing procedure without large welding deformation, since the VV has a double wall structure with extremely many welded parts. The total length of weld line ranges over 40 km. Prior to starting manufacturing, fundamental welding R&Ds had been performed by three stages. In the first stage, primary tests for screening welding method were performed. In the second stage, the trial welding for 1 m-long straight and curved double shell samples were conducted. The dependences of welding quality and distortion on the welding conditions, such as arc voltage and current, setting accuracy, welding sequence, and the shape of grooves were studied [6]. In addition, welding condition with low heat input was explored. In the last stage, heat input was confirmed and established by the trial manufacturing of the 20-degree upper half mock-up. Based on the results of the R&Ds including mechanical tests of welding joints, three welding types were chosen for the
double wall structure VV as shown in FIG. 2.

1) For butt joints of the inner/outer shells, plasma arc welding was applied to increase deposition and to suppress welding distortion, since the plasma arc welding has higher heat concentration than TIG welding. The plasma arc welding enables to reduce number of weld pass as compared with TIG welding.

2) The ribs are fillet-welded by Twin MAG welding. The Twin MAG welding enables to reduce welding distortion of the ribs by simultaneous MAG welding of both fillets. Consequently, it allows the ribs to keep precise angle because the all ribs should be set to the torus center direction to reduce bending stress in a vacuum condition.

3) MAG welding is applied for the continuous-plug welding to close the outer shell, since the MAG welding has higher deposition rate to reduce welding deformation. For the connection of stiffening ribs with inner/outer shells, one side must be closure-welded on the ribs by continuous-plug welding [7].

2.3. Trial Manufacturing of 20-degre Upper Half Segment

A trial manufacturing of the 20-degree upper half of the VV was carried out with the above welding types for each part in order to study welding distortion and procedure and to design constraint jigs for the welding. Welding robots were utilized for almost all welds. The welding conditions of arc voltage and current for welding positions, welding sequence, and teaching of the welding robots were studied.

At the first step, inboard and outboard segments were manufactured separately to confirm welding distortion for such large segments. The welding procedure of the outboard segment was complicated, since the port stubs have a variety of shapes. Welding distortion correction was locally performed for deformed part. Finally, the inboard and outboard segments were jointed. Figure 3 shows the mock-up of the 20-degree upper half of the VV. As a result of the trial manufacturing, the manufacturing procedure was successfully demonstrated without large deformation. Jigs for welding were optimized to suppress the welding distortions. Correction method for local welding distortion was also established [8].

2.4. Manufacturing of 40-degree Sectors

The manufacturing flow of the VV is shown in FIG. 4. Inboard and outboard segments of the 40-degree sectors are fabricated at a factory and delivered to Naka-site separately, since the size of the product is limited for the transport on a public road. Then, the inboard and outboard segments are jointed at Naka-site. At each welding stage in a factory, welding is performed on an appropriate jig on the basis of the mock-up manufacturing results. The jigs are fabricated with very high accuracy of ±0.5 mm to fit the designed curvature of the inner shell. Each part is fixed on the jig with clamps and bolts. Then, welding is performed. Welding distortion is confirmed without the jigs after each welding stage. Then, local distortion is corrected to the level of less than a few mm if needed. For the transport and the
connection of the inboard/outboard segments at Naka-site, a constraint jigs, which are part of those used for the welding at a factory, are fixed inside the segments separately. These jigs are also utilized for the pre-assembly of the inboard/outboard segments, and work as a constraint jig for the joint welding. Before the transport of the segments, glass beads blasting and buffing as surface finish are applied to the surfaces of the inner and outer shells, respectively. Especially, the buffing of the outer shell is required to reduce the emissivity (~0.15), which will be covered with the thermal shield.

The VV manufacturing started in December 2009. The manufacturing of the first VV 40-degree sector was completed after the inboard and outboard (IB/OB) connection on Naka site in May 2011 as shown in FIG. 5. Dimensional errors of the first product are roughly 2 mm at the inboard segment and 5 mm at the outboard. The key dimension of IB/OB was controlled within the tolerance of ±5 mm by using constraint jigs for each welding process. The dimensional errors found locally at the edges, which must be jointed with adjacent sectors, will be processed and jointed by welding with splice plate. The dimensional errors with welding distortion at the edges can be corrected less than 1 mm by the press working. The fabrication results of the first product shows considerable welding distortion around the top and bottom segments, which can be suppressed.

The manufacturing of the second and the third VV 40-degree sectors were also completed in December 2011 and March 2012, respectively. The averaged absolute errors of IB and OB inner surface position were measured on the several cross sections of four generatrixes, namely 5, 15, 25 and 35-degree, of the second and the third 40-degree sector. Reference points were set on the inner surface of IB and OB. The torus center was defined by the intersection of extended both planes. An optical theodolite was used to obtain the coordinate of each measured point. For the inner shell, obtained discrete data were processed and the inner surface of the product was reconstructed. By using least mean square method, the position and angle of the product was adjusted three dimensionally to minimize errors with respect to the designed shape. Then the dimensional errors were calculated. The absolute difference was obtained by comparing nominal (designed) value with actual value. The averaged absolute errors are less than 1 mm for IB and 2 mm for OB. The absolute directional errors of eight port stubs are less than 0.6 degree.

Manufacturing of up to the 6th 40-degree sector will be completed by the end of March 2013. The remaining sectors (7th 40-degree, two 30-degree and one 20-degree sectors) and will be accomplished by the end of March 2014.
3. Manufacturing and development of JT-60SA active cooling divertor

3.1. Design of Lower Divertor

The JT-60SA lower divertor is required to handle 41 MW heating power during 100 seconds and to be compatible with RH maintenance to exchange and/or repair it in the radio-active VV. In order to satisfy the first requirement of handling 41 MW heating power, 1) carbon armour tiles bolted on water-cooled heatsinks are applied to remove \( \leq 2 \text{ MW/m}^2 \times 100 \text{s} \) and transient pulse at 10 MW/m\(^2\) of heat load, and 2) Brazed CFC monoblock targets, which can remove 10-15 MW/m\(^2\) of heat flux continuously, are installed as vertical divertor targets. In order to satisfy the second requirement of compatibility with RH maintenance, divertor cassettes with fully water cooled plasma facing components are developed to enable to repair and replace new one. Each divertor cassette, which allows its installation and removal by RH maintenance, covers a 10-degree sector in the toroidal direction \([9]\).

The objectives of JT-60SA divertor are the support of ITER divertor experiments and the supplement of DEMO divertor design bases. Therefore, JT-60SA divertor has private dome and “V-shaped” corner at the outer divertor to enhance particle recycling and radiation similar to the design concept of ITER divertor. The divertor pumping capability comparable to that in ITER will be implemented to obtain wider particle control range. The divertor geometry of JT-60SA is optimized to allow ITER like plasma configuration and also higher elongation and triangularity plasma which are required for high beta plasma operation in DEMO. Divertor plasma performance of lower divertor geometry with vertical targets for ITER-like plasma configuration had been assessed by using simulation codes. Inner divertor target was moved upward, outer target was moved downward and height of private dome was reduced to increase plasma elongation and triangularity. Height of private dome and size and position of pumping slots were adjusted to keep particle control capability and expected heat flux less than 15 MW/m\(^2\) \([10, 11]\).

Figure 6 shows the latest configuration of a lower divertor with a typical plasma configuration. The key points of design are (i) divertor cassette and RH manipulator for the cassette shall be designed to be a small mechanism to be inserted (and to be deployed) through a horizontal port with 0.66 m width, and (ii) the divertor cassette shall be removed and installed only with access from the plasma side. A part of carbon armour tiles shall be removed by RH manipulator to enable access to fixing bolts of a cassette and coolant pipe connection. Coolant pipe connections located under the top of outer baffle are cut through the access holes between heatsinks by using similar tools for ITER blanket pipe connection. Torque of the downsized manipulator is not enough for moving the cassette weight of 800 kg with a fully expanded telescopic arm. Therefore, a cassette is moved by built-in mechanism. Then, the cassette shall be lifted and transported to the large horizontal port for maintenance by the rail-vehicle system similar to ITER blanket RH system. The cassette can be carried out from the vacuum vessel by the
transporter inserted through the horizontal port.

Plasma facing components such as vertical targets, baffles and dome have been modularized to be assembled on the divertor cassettes. Carbon armour tiles bolted on water-cooled heatsinks are applied for baffles and private dome, where the maximum steady state heat load including plasma radiation is less than 2 MW/m². The CFC monoblock targets will be installed partially for a part of outer targets at the start of “initial research phase” of 21.5 MW heating power during 100 seconds. Then they will be replace bolted CFC tiles for inner and outer targets during “initial research phase” [12].

3.2. Development of Divertor Cassettes

Technical issue for the divertor cassette manufacturing is to establish a manufacturing procedure with the required accuracy of ±1 mm, since the divertor cassettes must be precisely installed to avoid local high heat flux at the edge of plasma facing components, which means the tolerance of 0.5-1.0 mm at the surfaces of plasma facing components.

Trial manufacturing of the full-size divertor cassette frame was carried out in order to study welding procedure for the small welding distortion. Welded frame shrunk in radial direction. After the heat treatment of stress relieving, the tolerance in machining was achieved ±0.1 mm. The combination of TIG and MAG welding and adjustment of parts size reduced welding deformation of the cassette frame. In the latest mock-up, radial shrinkage reduced to ~5 mm, which is within the margin for machining as shown in FIG. 7.

Water flow test of coolant pipes was done using a mock-up including heatsinks in order to demonstrate water flow without water hummer and air pocket and investigate water pressure drop as shown in FIG. 8. Pressure drop and parallel distribution of cooling channels had been measured with the full size mock-up for cooling pipes and channels in heatsinks. Filling and draining of water procedure had been confirmed. Distribution of cooling water in parallel channels is enough uniform. Total pressure drop exceeds 0.6 MPa from the expected result of water flow analysis. The branch pipes of the mock-up almost penetrated into the header pipes. These sticking out of the branch pipes occurred pressure drop in the headers. It could be reduced by improvement by branch pipe fitting at headers.

![FIG. 7. Mock-up of a divertor cassette frame.](image1)

![FIG. 8. Cooling water test with a mock-up.](image2)
3.3. Manufacturing of Divertor Cassettes

As a result of the trial manufacturing, the manufacturing procedure with the required accuracy of ±1 mm was successfully established. Then, the manufacturing of divertor cassettes has been started. Figure 9 shows the preassembly of three divertor cassettes including heatsinks for inner/outer targets, private dome and inner/outer baffles. The preassembly of 4 divertor cassettes was completed. The welding of 16 divertor cassette frames was finished. The manufacturing of 36 divertor cassettes will be completed in March 2013.

4. Development of Acceptance Inspection for Monoblock Targets

Manufacturing technique of brazed CFC monoblock targets for a divertor target has been significantly improved by precise control of tolerances within several ten μm and with a change of inside treatment from metallization to titanium coating inside 10 CFC blocks [12, 13]. Figure 10 shows the first CFC monoblock target fabricated in March 2011. After that, the manufacturing of more than 100 CFC monoblock targets in total is ongoing.

The heat removal performance of the CFC monoblock target was successfully demonstrated on the JAERI Electron Beam Irradiation Stand (JEIBIS). The surface temperature of the CFC monoblock target was able to keep around 1700°C against heat load of 15 MW/m². This acceptance inspection has been employed on 25 CFC monoblock targets in total. However, it is required to shorten the inspection hours for more than 1000 CFC monoblock targets.

Therefore new infrared thermography test by changing the cooling water temperature has been developed as the alternative acceptance inspection to the heat load test with the JEIBIS. In this inspection, cooling water was switched from hot (95°C) to cold (5°C) water. The typical cooling time (90°C → 60°C) of the five surface position of a monoblock was measured. The high heat removal performance of the CFC monoblock target was confirmed by comparing its cooling time with the normal cooling time of ~0.6 s of the standard CFC block which has been verified by the JEIBIS. Figure 11 shows the infrared thermography picture of the fifth monoblock target at a cooling water temperature of 95°C.

FIG. 9. Preassembly of three divertor cassettes.

FIG. 10. The first CFC monoblock target.

FIG. 11. The infrared thermography test picture of the fifth monoblock target. Two side views can be observed with mirrors in addition to the top view (center).
5. Conclusions

The manufacturing procedure of the JT-60SA vacuum vessel (VV) was established through the welding R&D and a trial manufacturing of the 20-degree upper-half mock-up. The first VV 40-degree sector was completed in May 2011. The key dimension of IB/OB was controlled within the tolerance of ±5 mm by using constraint jigs for each welding process. The manufacturing of the third VV 40-degree sector with improved fabrication accuracy was completed in March 2012. The averaged absolute errors of the second and the third VV 40-degree sectors were controlled to be less than 1 mm for IB and 2 mm for OB after the suppression of welding distortion around the top and bottom segments based on the fabrication results of the first product.

Divertor cassettes with fully water cooled plasma facing components were designed to realize the JT-60SA lower single null closed divertor. The divertor cassettes, which will be used in the high radio-active VV, have been developed to ensure compatibility with remote handling (RH) maintenance. The manufacturing of divertor cassettes with typical accuracy of ±1 mm has been successfully completed. Brazed CFC monoblock targets for a divertor target have been manufactured by precise control of tolerances inside CFC blocks. The infrared thermography test of monoblock targets has been developed as the simplified acceptance inspection for a lot of monoblock targets.

Acknowledgements

The authors would like to thank TOSHIBA Corporation for their support of the VV manufacturing, KINZOKU GIKEN CO., LTD. for their support of the divertor cassettes manufacturing, and KAWASAKI HEAVY INDUSTRIES, LTD. for their support of the CFC monoblock target manufacturing.

References