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MHI's Efforts towards ITER - Challenges to Build Large-size High-performance Superconducting Coils -


Heat treatment furnace for TF coil conductors

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At present, the ITER Organization undertakes the design, construction, operation, decommissioning, etc. of equipment/facilities of ITER (International Thermonuclear Experimental Reactor), while seven participants handle the manufacturing under an adopted "in-kind system": in addition, equipment/facility manufacturing is under way. Japan has been assigned to develop a part of the divertor systems, plasma heating systems, plasma diagnostics, and other important items including Toroidal Field (TF) coils to generate a magnetic field for plasma confinement and Mitsubishi Heavy Industries, Ltd. (MHI) is involved in nearly all of these. This paper reports on the results as well as the present status of verification tests, etc. for the manufacturing of actual TF coils and briefly explains our activities for the divertor systems indispensable for sustaining stable plasma confinement.

1. Introduction

The development of nuclear fusion energy has just taken a new step as the construction of ITER (International Thermonuclear Experimental Reactor) has started. In accordance with the then US-Soviet Summit (Reagan-Gorbachev) Joint Declaration of 1986, the ITER project started with Conceptual Design Activities (CDA) in 1989; the participants in the CDA were the USA, former Soviet Union (Russia), Europe, and Japan. From 1992, for about nine years in the Engineering Design Activities (EDA), detailed design, verification tests for manufacturing and new technology development were carried out.

In 2005, Saint-Paul-lès-Durance of France was chosen as the construction site; this site is adjacent to the Cadarache Research Center of CEA (the Alternative Energies and Atomic Energy Commission).

On November 21, 2006, a minister-level meeting was held and the ITER Agreement was signed at the Élysée Palace in Paris. This minister-level meeting was followed by the first provisional ITER Council, and approval to bring the ITER international Fusion Energy Organization (ITER Organization) into being as an international legal entity was obtained under the provisional application of the ITER Agreement. Inauguration of the ITER Organization was officially put into effect based on the agreement on the establishment of the ITER Organization on October 24, 2007 via the ratification of the participants (Japan, the US, Russia, China, Korea, India, and the European Union (EU)). An in-kind contribution system, where the ITER Organization undertakes the design, construction, operation, decommissioning, etc. of equipment/facilities while seven participants deal with the manufacturing of equipment/facilities, was adopted and, at present, manufacturing of equipment/facilities is under way by participants.

Japan has been given the role of supplying Toroidal Field (TF) coils to generate the

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magnetic field for plasma confinement as well as high-tech equipment such as the divertor system, some plasma heating systems (such as RF heating and NBI systems), and some plasma diagnostics (such as the impurity monitoring system and plasma density measurement system etc.). MHI is involved in almost all of these objectives. In particular, for TF coils, which are the largest superconducting coils in the world, prototype tests are almost complete and manufacturing of actual coils has just started. This paper describes the results and present status of verification and other tests for the manufacture of actual TF coils and gives an outline of our activities for an ITER divertor indispensable for sustaining stable plasma confinement.

2. Outline of ITER and TF Coils

(1) Outline of ITER[1]

The ITER mission is to verify self-ignition of fusion plasma and sustain long burning which is indispensable for tokamak-type nuclear fusion power generation as well as nuclear fusion reactor engineering technology. ITER plays an important role in acquiring/accumulating the data that contributes to such areas as the design, manufacture, and construction of a demonstration reactor for the verification of future power generation. The basic parameters of ITER are shown in **Table 1**, utilizing deuterium and tritium as fuels, fusion power of 500MW, plasma burning time of 400 or more seconds, and a fusion energy gain factor (Q)* of 10.

*Fusion energy gain factor (Q): Ratio of fusion output energy to input energy

Table 1 Main Specifications of ITER

Fusion power	up to 500MW
Plasma burning time	400 seconds – 3,000 seconds
Fusion energy gain factor	up to 10
Plasma current	up to 15MA
Plasma volume	up to 840m^3
Machine size dimensions	About 30m in diameter and 30m in height
Total wight of main components	About 23 thousand tons

(2) Outline of TF coils

ITER has adopted the tokamak-type magnetic field confinement system where the magnetic field generated by the plasma current flowing through the doughnut-shaped vacuum vessel confines plasmas together with another magnetic field generated by the coils arranged vertically in the doughnut direction. Here, the doughnut direction is referred to as the toroidal direction, and coils arranged vertically to the doughnut direction are called toroidal field coils since these coils generate magnetic fields in the toroidal direction. On the other hand, the circumferential direction of the doughnut cross-section is referred to as the poloidal direction and these coils generate a magnetic field in the poloidal direction, so they are called the Poloidal Field (PF) coils.

The TF coil assembly, generating a magnetic field at a maximum of 11.8T and of 5.3T in the plasma center, consists of 18 D-shaped coils set at even intervals in the toroidal direction. The field tolerance for keeping plasma confinement is within the order of a few millimeters and the required accuracy is as high as ten-thousandths of a millimeter. This also involves the dimensional accuracy of TF coils, which require such accuracy in the order of several millimeters against a 16m-tall 9m-wide welded structure. TF coils are in an extra thick plate welded structure, which can endure a tremendous electromagnetic force being exerted on it, and the structural material is special stainless steel since it is used in the range of a cryogenic temperature such as -269ºC.

Figure 1 shows the structural concept of ITER TF coils. TF coils comprise a winding pack (WP) of built-up multi-layered superconductors and a toroidal field coil structure (TFCS) to encase the WP. The WP consists of seven double pancake (DP) layers and each DP is a composite of a conductor, groove-worked radial plate (RP) and cover plate (CP) to seal the groove. The TFCS to encase the WP is divided into subassemblies called AU, AP, BU, and BP, to each of which several basic segments are joined by welding. Accessories such as support structures to connect co-adjacent TF coils are attached to AU and BU by welding.

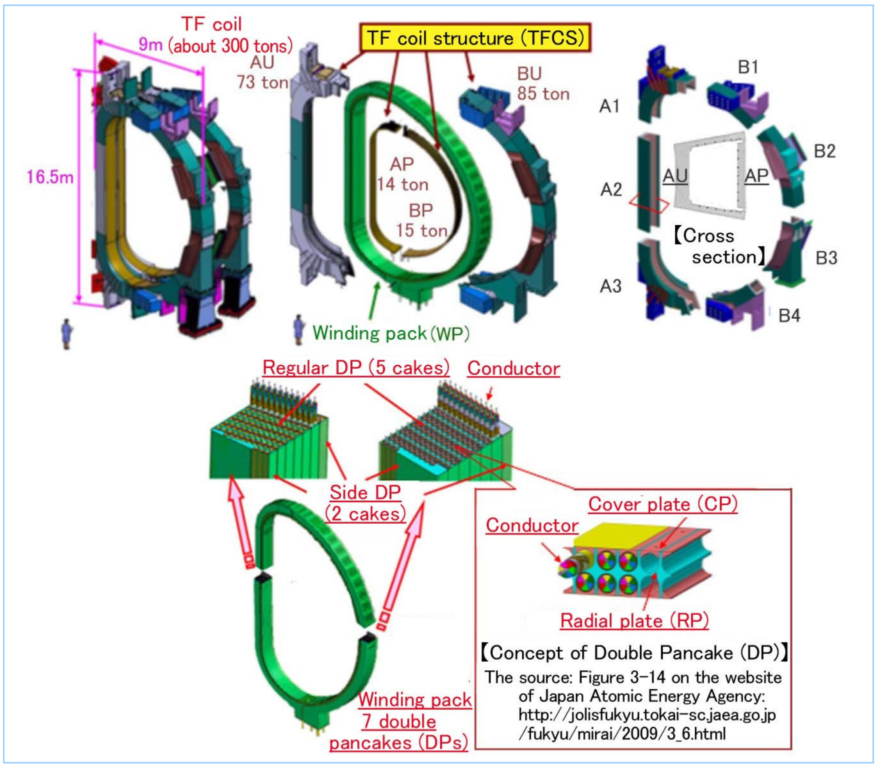

Figure 1 Concept of toroidal field coil structure
(courtesy of: The Japan Atomic Energy Agency)

3. Technical issues on TF coil manufacturing

Since the structural material of TF coils is special stainless steel for cryogenic use, it is necessary to establish welding, machining, and other base technologies suitable for such material in terms of its properties and then manufacturing processes that satisfy the specifications required for (the accuracy of) ITER.

(1) Accuracies required for TF coils

The required accuracies of TF coils are 1 mm for both the profile and flatness of TFCS/DP, 0.4 mm for the surface flatness of the interface between co-adjacent coils and 34,000±5 mm for the perimeter of RP.

Furthermore, as for the conductor material of TF coils, high magnetic field-resistant Nb3Sn is adopted, requiring the manufacturing processes to be managed so as not to put too much strain (0.1% or more) on wires heat treated to be superconductive.

(2) Characteristics of structural material for TF coils[2][3]

The structural materials of TF coils have been developed, aiming at 1,000MPa of 0.2% proof stress at -269ºC and a fracture toughness of 200MPam1/2. For the straight portion of the D-shaped coils on which a considerable force is exerted, a highest-strength material called JJ1 is used. For the other portions, three steel types, SUS316LNL, LNM, and LNH are used, whose nitrogen contents are different for varying strength requirements. **Table 2** shows the chemical compositions and mechanical properties of JJ1- and SUS316LN-based material.

(3) Welding technology

It is difficult for the structural material of TF coils to be welded. As shown in Table 2, since larger quantities of nitrogen were included to secure the strength of the material under the cryogenic circumstance, porosities would easily occur due to gasification of nitrogen during welding. These materials are a kind of full austenitic steel and hot cracks are prone to occur during welding.

Based on the characteristics of the materials used for TF coils, electron beam (EB) welding, laser beam (LB) welding and narrow-groove TIG welding were adopted as low-heat input welding to minimize welding deformation. It is necessary to optimize their process conditions and establish the process for each method. For this purpose, various kinds of primary tests, process verification tests with a small-scale mock-up and with a full-scale mock-up were carried out.

Table 2 Chemical composition and mechanical properties of structural materials of TF coil

Material	C	Si	Mn	P	S	Ni	Cr	Mo	N	C+N	Tensile strength (MPa)	Yield strength (MPa)	Fracture toughness value ($MPam^{1/2}$)
JJ1	0.030 or less	0.75 or less	9.00 - 11.00	0.035 or less	0.015 or less	11.00 - 13.00	11.00 - 13.00	4.00 - 6.00	0.21 - 0.27	-	> 620	> 300	> 180
											> 600	> 280	> 180
316LNL	0.030 or less	0.75 or less	2.00 or less	0.03 or less	0.020 or less	10.00 - 14.00	16.00 - 18.50	2.00 - 3.00	0.05 - 0.120	0.080 or more	> 520	> 210	> 180
											> 480	> 205	> 180
316LNM	0.030 or less	0.75 or less	2.00 or less	0.03 or less	0.020 or less	10.00 - 14.00	16.00 - 18.50	2.00 - 3.00	0.100 - 0.170	0.130 or more	> 550	> 245	> 180
											> 520	> 230	> 180
316LNH	0.030 or less	0.75 or less	2.00 or less	0.03 or less	0.020 or less	10.00 - 14.00	16.00 - 18.50	2.00 - 3.00	0.150 - 0.220	0.180 or more	> 580	> 280	> 180
											> 560	> 260	> 180
SUS316LN (JIS)	0.030 or less	0.75 or less	2.00 or less	0.045 or less	0.030 or less	10.50 - 14.50	16.50 - 18.50	2.00 - 3.00	0.12 - 0.22	-	-	-	-
											-	-	-

Note 1: P+S<0.050 mass%
Note 2: Values of tensile strength and yield strength are shown at room temperature.
Note 3: Fracture toughness   is obtained at 4K. (Plate thickness, top: Less than 200 mm, bottom: 200 mm or more)

(4) Machining technology

The structural material of TF coils is also less workable in machining (cutting) than ordinary stainless steel (SUS304) due to its nitrogen content. TFCS and RP have complex shapes and it is necessary for greater machining efficiency and less deformation due to processing to select the suitable tools, set proper machining conditions and establish appropriate work processes. Thus, as in welding technology, primary tests to understand workability and process verification tests with the small-scale mock-up and the full-scale mock-up were performed.

4. Technology verification

Results of R&D on welding and machining technologies relating to TFCS/RP manufacturing are roughly as follows:

4.1 Technological verification for TFCS manufacturing

Before actual production of TFCS, the tests were conducted step by step, which produced successful developments such as the optimization of the welding conditions to prevent porosity and the decision regarding the welding procedure to minimize the welding deformation.

(1) Primary tests

For welding of TFCS, of which the thickest parts are more than 200mm, a low heat input welding process such as narrow-gap TIG welding and electron beam (EB) welding was selected and its applicability was examined.

Narrow-gap TIG welding was tested, targeting higher welding efficiency, and the optimized welding condition was found to obtain sound weld metal at the deposition rate of 20g/min. in the flat position.

Electron beam (EB) welding was tested to achieve thicker weld metal, and the optimized welding condition was found to obtain sound weld metal without porosity at a thickness of 40 mm.

(2) Process verification tests with small-scale mock-up

Using a 1-meter-long small-scale mock-up which has a cross section equivalent to that of an AU straight portion (**Figure 2**), a test was conducted to check welding deformation and establish a welding procedure that can minimize welding deformation. Primary results are described as follows:

- In outer plate/side plate joint welding tests, the deformation was minimized by EB welding and narrow-gap TIG welding from both sides.
- In joint welding tests between segments, the application of the both-side welding procedure could minimize angular deformation of the side plate and outer plate.
- No indication was detected by nondestructive inspection or no defects including micro-cracks were found by cross-sectional observation, proving flawless welding.

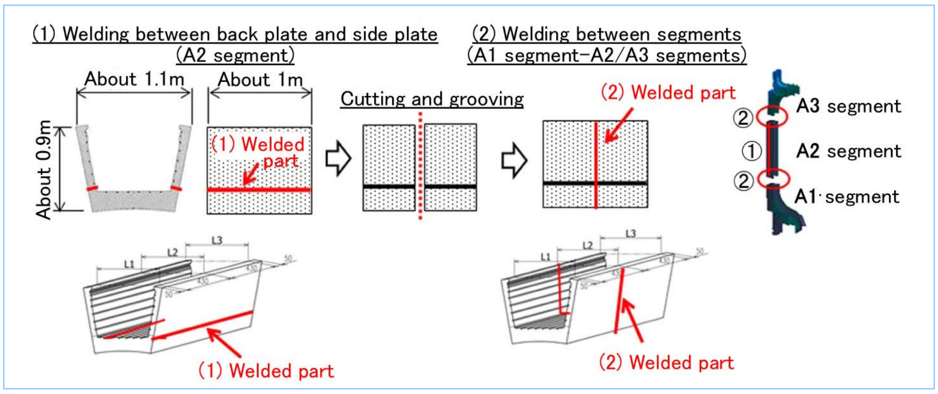

Figure 2 Small-scale mock-up test

(3) Process verification tests with full-scale mock up

To establish the manufacturing process for an actual TFCS, a full-scale mock-up of AU curved and straight portions was manufactured based on the result of primary and small-scale tests. In addition, a simulated part of BU was also fabricated and welding between AU and BU subassemblies was tested.

In testing, deformation was kept balanced by welding from both sides instead of using a jig to firmly restrain welding deformation. The AU straight portion was manufactured by combined processes of EB welding and narrow-gap TIG welding and, for the AU curved portion, the process of narrow-gap TIG welding from both sides was applied due to its shape. **Figure 3** shows the appearance and deformation results of a test-manufactured mock-up.

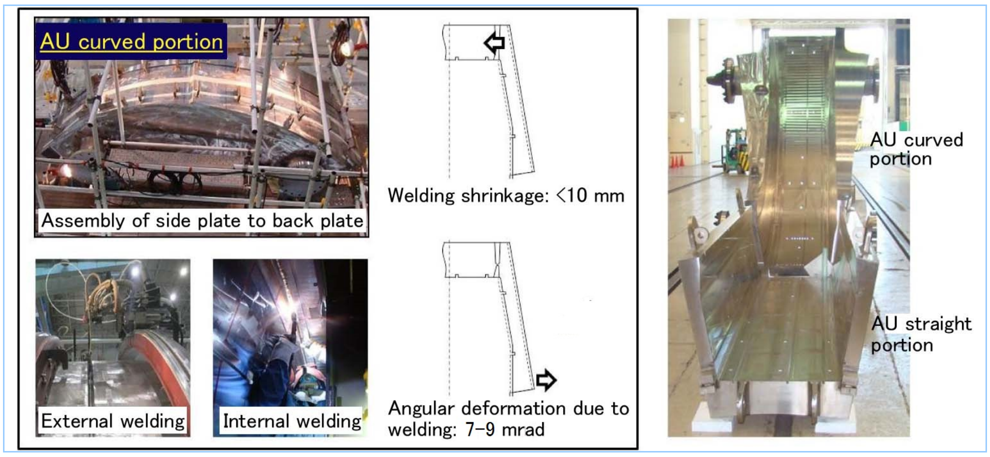

Figure 3 Full-scale, partial mock-up test (AU curved and straight portion)

4.2 Verification tests of RP manufacturing technology

The RP, into which TF coil conductors are set is formed from forging plate by grooving process, and about 80% of the forging plate is machined and a huge amount of cutting chips are generated. The material is high strength, high-nitrogen stainless steel called SUS316LNH (see Table 2), which has so far never been used by us for welding and is much harder to weld and machine than ordinary stainless steel. Process verification was, therefore, given after welding and cutting conditions were selected and the machining method and assembling procedure were established for full-scale manufacturing. Major results are given below.

(1) Primary tests

[1] Selection of the welding work conditions for RP

In consideration of the RP weld method, to weld 120mm-thick plate for a large D-shaped coil (14m×9m), rather than EB welding which requires a vacuum chamber, a combined process of laser beam (LB) welding and narrow-groove TIG welding was adopted. The applicable range of LB welding using a 30kW fiber laser (rated among the world's largest-output power for general purposes) was verified and it was decided to weld a 50-mm thickness from both sides. For the remaining part, narrow-groove TIG welding was to be used and element tests indicated good prospects of securing the necessary flatness. **Figure 4** shows a macroscopic cross section of the welded part.

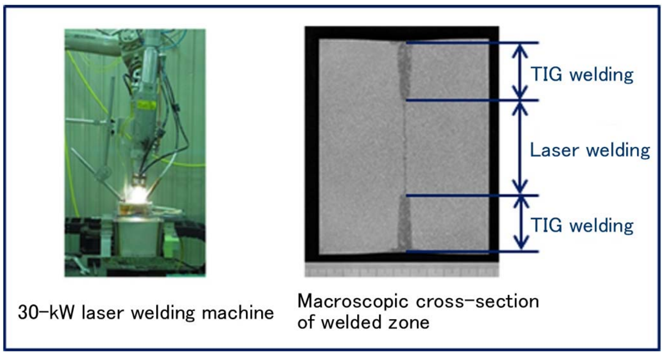

Figure 4 Primary tests for RP welding

[2] Selection of machining conditions

With a view to establishing a grooving method, machinability and life verification tests were conducted using several kinds of tools, and then the tools that achieved good results were tested for verification of machinability to improve cutting conditions in rough machining.

- Machinability and life verification tests

Figure 5 shows the processing performed during verification tests. The grooving process is roughly divided into four phases and **Table 3** shows the result of the rough machining phase that shares much of the processing (about 70%). Among the tools used, only one type exhibited good machinability.

- Tests for the improvement of cutting conditions in rough machining

Tools that exhibited good results in the above-mentioned tests were further examined, aiming at the improvement of their machinability. As a result, the cutting amount per minute could be improved 1.35 times and tool life also increased to 40 minutes or more, thus virtually assuring the prospect of stable machining (**Figure 6**).

Table 3 Crude processing tool selection result

Test No.	Tool maker	Tool to be used	Stability	Amount of cutting powder discharged (cc/min.)	Tool life (min.)	Overall rating
1	Company A	φ40 shoulder cutter	Stable	61.2	20 or more	Excellent
2	Company B	φ25 plunge cutter	Stable	36.0	13	Bad
3	Company C	φ25 high feed cutter-1	Stable	24.7	20	Moderate
4	Company C	φ30 high feed cutter-2	Stable	50.0	25	Moderate
5	Company D	φ42 high feed cutter	Defective	81.4	4	Bad

Figure 5 Primary tests for RP grooving

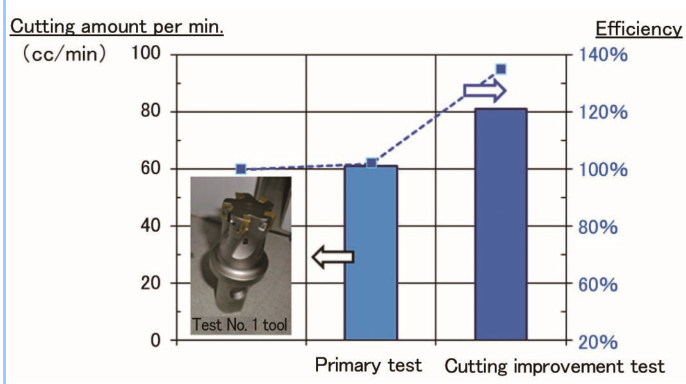

Figure 6 Improvement of cutting performance in Test No. 1 tool (Table 3)

(2) Process verification tests with small-scale mock-up

Results concerning trial manufacturing of RP segments are described as follows:

In these trials, materials prepared by profile forging were machined into the final cross-sectional shape to verify the machining property as well as to examine the process for controlling deformation. Primary results are described as follows:

- φ40 plunge machining performed stable machining. Moreover, basic data for further elongation of tool life could also be obtained.
- The flatness, with a reading of 0.39 mm in Test #1 and 0.14 mm in Test #2, could be kept within its tolerance of 1 mm. For full-scale manufacturing application, matters to be improved, etc., could also be extracted, allowing high-accuracy machining process databases to be thoroughly prepared.

(3) Process verification tests with full-scale mock-up

To verify all manufacturing processes of RP, the full-scale D-shaped sRP (s is an abbreviation of side) was conducted to verify the manufacturing process.

As shown in **Figure 7**, the AU side consists of four segments and the BU side, six segments. Each segment was processed while checking the flatness of RP during processing. One segment is joined to another by TIG as well as LB welding so that four sectors are to be formed before the D-shaped processing. Final machining of the D-shape is carried out, using specialized machinery as shown in **Figure 8** (a), after the conductor length of heat-treated winding was checked. The final flatness of the full-scale D-shaped sRP was 0.95mm, which satisfied the required tolerance of 1mm. The groove length was also no more than the tolerance of ±0.01. The appropriateness of the machining processes adopted here could, therefore, be verified.

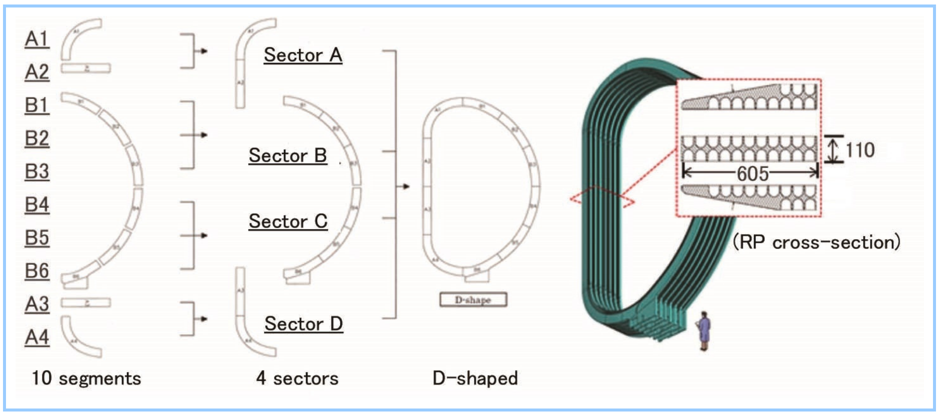

Figure 7 Concept of RP structure (Courtesy of: The Japan Atomic Energy Agency)

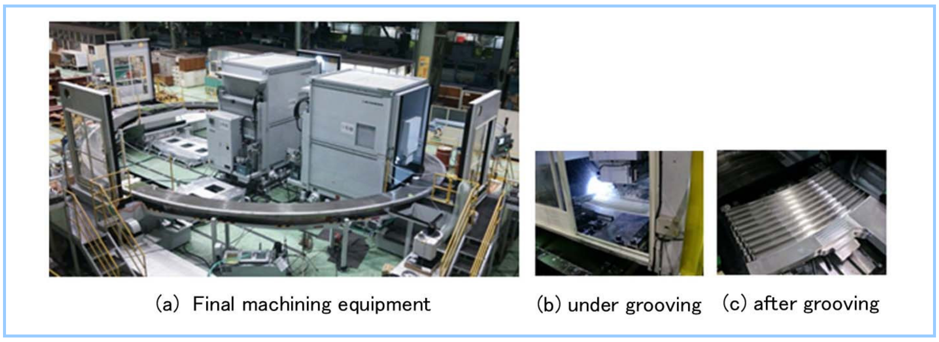

Figure 8 Final machining of sRP full-scale mock-up

5. Current status of actual production of TF coils

The first unit of the TF coil was contracted in August 2012, and the contracts for manufacturing the five units of TF coils in total were finally made. While learning the welding procedure and verifying the work process with a variety of mock-ups, manufacturing of an actual radial plate (RP) and TF coil structure (TFCS) started in October 2013 and April 2014, respectively.

In TF coil production, with winding pack fabrication entrusted to Mitsubishi Electric Corporation, MHI takes the role of manufacturing the structure encasing a winding pack of TF coils (TFCS) and RP into which the conductor is placed, heat treatment of conductors, welding of cover plates (CP), and final assembly. Part of the structure (BU and BP) is manufactured by Hyundai Heavy Industries Co., Ltd.

At the Main and Futami Plants of MHI Kobe Shipyard & Machinery Works, full-scale fabrication is under way, using the equipment necessary for TF coil production that is manufactured and installed there. Various specialized facilities for RP fabrication (LB welding systems, automatic TIG welding systems, and the final machining system of RP) were prepared in the Main Plant. In the Futami Plant, in addition to existing welding systems and machines, the coil winding machine, heat treatment furnace for conductors, conductor transferring machine, CP welding systems electrical insulation machines, and impregnating equipment were prepared and these machines have operated to manufacture the actual product. For example, typical machines are shown in **Figure 9**; these machines are the heat treatment furnace manufactured by MHI and the winding machine manufactured by Mitsubishi Electric Corporation.

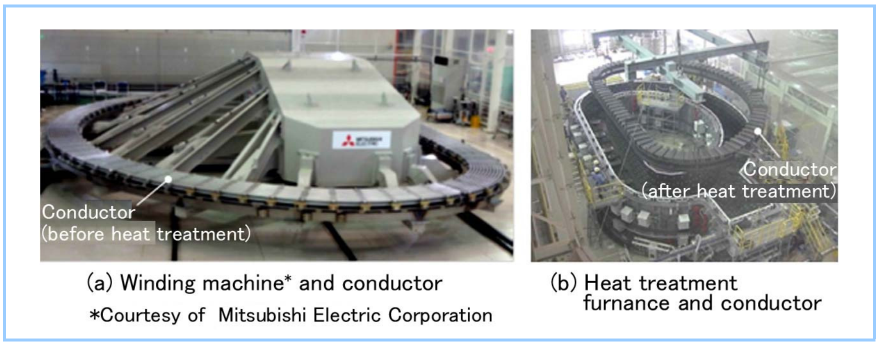

Figure 9 Example of special equipment for manufacturing TF coils

As for TFCS, mock-up tests were completed and actual product fabrication is under way based on test results.

RP fabrication has also made steady progress, with 140 segments or a two-units-equivalent of 350 segments (5 units × 7 RPs × 10 segments) already manufactured and some 10% of 140 sectors (5 units × 7 RPs × 4 sectors) already fabricated or now being machined. **Figure 10** shows TFCS and RP manufactured.

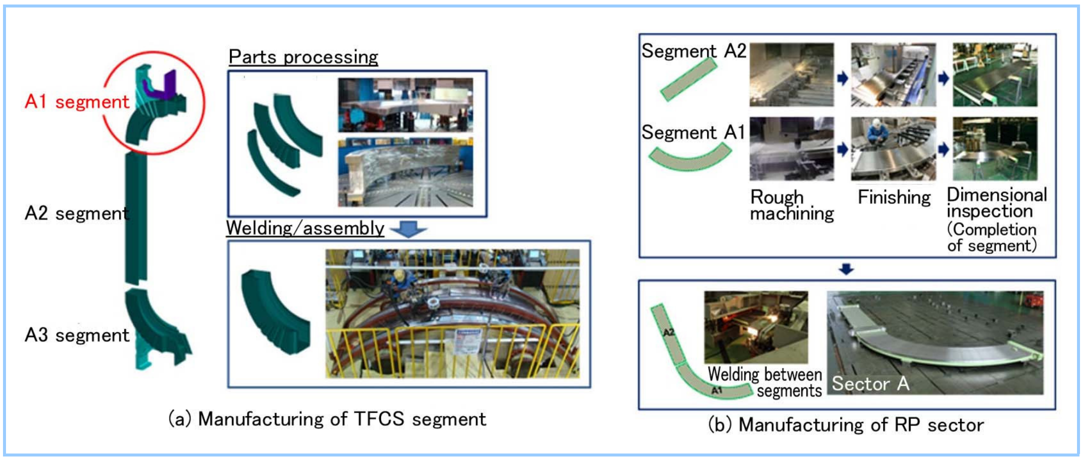

Figure 10 Full-scale manufacturing status of actual product

6. Activities regarding ITER divertor

The divertor infusion reactors, functioning to extract helium ashes from fusion product, unburnt fuel particles, and impurities, is one of the important components in ITER for securing stable confinement of plasma. It is necessary to endure a high heat load of tens of megawatts/m2 on the divertor's surface facing plasmas.

As shown in **Figure 11**, divertor development has been taken charge of by Japan, Europe, and Russia, and Japan is to share the Outer Vertical Target (OVT).

MHI participated in the OVT prototype program, and the mock-ups of the Plasma Facing Unit (PFU) as a component to receive the high heat flux and Steel Support Structure (SSS), which supports the PFU, were fabricated to check manufacturability and so on. **Figure 12**(a) shows the external appearances of the mock-ups. The PFU was tested for thermal resistance using the high heat load test facility at the Efremov Scientific Research Institute of Electrophysical Apparatus (NIIEFA), Russia, and our PFU met the specific requirements of the heat load for the ITER divertor and was first qualified in the large-sized PFU. Figure 12(b) shows the external appearance after a thermal resistance test.

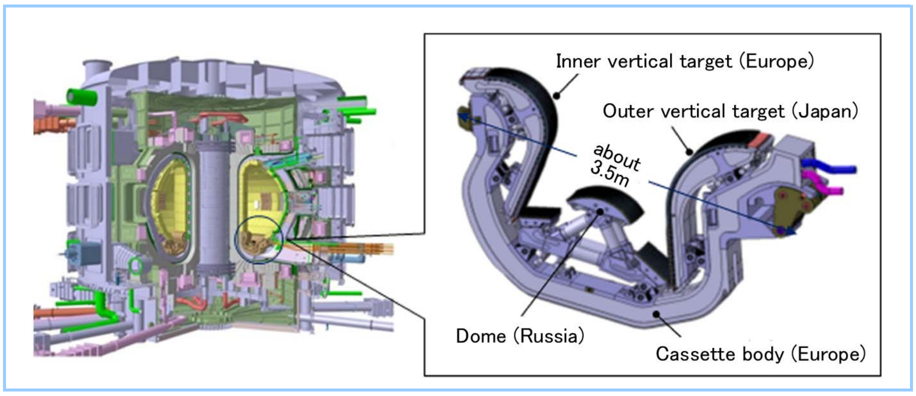

Figure 11　Structural concept of an ITER divertor
(Courtesy of: The Japan Atomic Energy Agency)

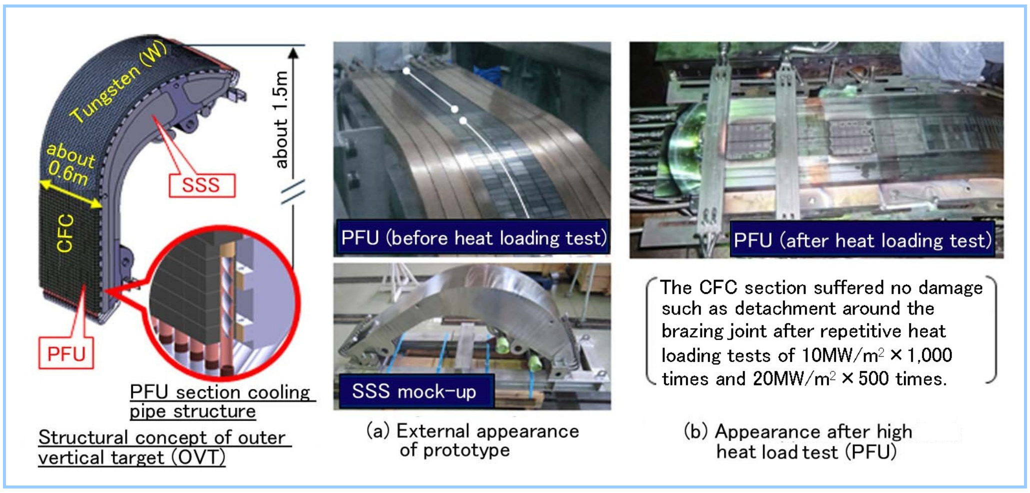

Figure 12　Trial manufacture and tests of an outer vertical target prototype of a divertor
(Courtesy of: The Japan Atomic Energy Agency)

Carbon fiber composite (CFC) has so far been used for the high heat load region of PFU, but CFC was replaced with tungsten (W) due to the recent design change, coming from a reevaluation of the behavior of impurities in plasmas. According to the design change, a new mock-up test of W-PFU is now being performed.

7. Conclusion

Manufacturing of ITER TF coils is very challenging because we have no experience of such a large-size coil, about 16.5m in height and 9m in width with high tolerances of 0.1%, which are the characteristics of the largest superconducting magnets in the world. We started to manufacture the actual TF coil based on technologies established through basic tests and verification tests.

We are making efforts to establish manufacturing technologies for the ITER divertor with collaborative support of the Japan Atomic Energy Agency.

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