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Completion of the First ITER Toroidal Field Coil in Japan

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In the last report, we announced the completion of the first coil case structure for ITER Toroidal Field (TF) coil [1]. Since then, the assembly of winding pack (WP) with the coil case has been completed. In this paper, we report the completion of the first ITER TF coil in Japan. The successful assembly of TF coil was achieved by developing manufacturing techniques to overcome some challenges; such as: (i) positioning of WP inside coil case to optimize deviation in current center line (CCL), a magnetic property, of a coil under a few millimeters, (ii) satisfying the tolerances on interfaces with other coils and supports, sometimes sub-millimeter, in spite of welding deformation during coil case welding, (iii) impregnation of narrow gaps between WP and coil case with high viscosity charged resin, and (iv) tracing CCL through the assembly process and transferring the information to the coil case.

ITER TF magnet is a D-shaped coil consisting of superconducting WP enclosed in a massive austenitic stainless-steel case with a height of 16m and a width of 9m. A set of 18 TF coils will be installed in the tokamak to create a magnetic field to confine the plasma within the donut-shape vacuum vessel. Among the set of 18 coils, 8 TF coils along with a spare are manufactured by Japanese domestic agency (DA) and remaining 10 TF coils are manufactured by EU DA. In Japan, TF coil is assembled in vertical posture with straight portion of D-shape facing the bottom to realize the bilateral symmetricity of the coil. The assembly is performed in the following steps; 1) insertion of WP into straight portion of coil case, 2) positioning of curved portion of coil case and welding with straight portion, 3) closure of coil case with inner cover plates, 4) impregnation of gap between WP and coil case, 5) final machining of interface surfaces and holes, and 6) dimensional inspections and electrical tests. It is important that generated magnetic field be toroidally uniform; therefore, those 18 coils shall have the same shape and the magnetic property to be assembled evenly around the vacuum vessel regardless of differences in manufacturing strategies, tooling and postures between two DAs. In order to achieve common requirements, unprecedented and severe tolerances are defined on both the CCL and the interfaces.
The CCL of a coil is the center line of an equivalent single turn coil, which has the same magnetic field properties at far away locations. The CCL shall exist within 2.6mm diameter circle over the extent of straight portion of more than 7m while keeping sufficient gaps between WP and coil case for impregnation [2]. In order to position WP to accommodate both requirements, the target WP position within coil case was assessed in advance using the individual dimensional inspection data of WP and coil case [3]. The WP position was monitored by laser tracker during insertion so that the fine adjustment of 0.1mm order was possible. After positioning of WP, measurement results of gaps between WP and coil case showed the validity of the prior assessment.
To install 18 TF coils around ITER vacuum vessel to create uniform magnetic field, very severe structural tolerances are defined at interfaces. Since the welding deformation has large impact on the positions and shapes of interfaces, extra materials were left on critical interfaces to be machined to nominal after welding. On the other hand, leaving too much of extra materials will lead to longer machining duration. To avoid unnecessary schedule delay, amounts of extra materials were minimized. Where extra materials were found not sufficient, two DAs collaborated to compensate all 18 coils in a common deviation under guidance of ITER Organization (IO) to harmonize the shape of final coils. This harmonization strategy was a great way to manage two conflicted issues, manufacturing schedule and accuracy, and a big achievement as international collaboration project.
For impregnation of the gaps between WP and coil case, there was a concern in breakage of the seal between WP and coil case at the terminal region, where conductor ends and instrumentation wires are extracted from

WP, during evacuation before impregnation and pressurization after resin injection due to the relative movement of WP with respect to coil case. To prevent the relative movement, partial vacuum chamber is installed over the terminal region to balance the pressures on both sides of the seal. The pressure balance was monitored by pressure gauge and feedbacked to pressure control inside the partial vacuum chamber. However, filler added to impregnation resin as crack prevention increased viscosity of resin and therefore, the resin's internal pressure during resin injection. For the first coil, adjustment of pressure balance required full attention of operator since resin's internal pressure directly affected the pressure inside coil case. For the second coil, addition of relay tank between coil case and resin injection system prevented sudden change of resin pressure and improved manageability of pressure balance.
Since WP of TF coil is enclosed in coil case, CCL positional information needs to be transferred to reference points on coil case. As mentioned earlier, TF coil is assembled standing on straight portion of D-shape, resulting in gravitational deformation in WP. The amounts of deformation are about 1mm at the straight portion and 4mm at the curved portion. After coil case welding, deformation of WP is corrected by pushing curved region of WP against coil case by bolts [2] in accordance with the prior assessment using structural analysis. However, the resulted WP shape differed from the prior assessment. Since the WP is pushed against coil case, residual stress in coil case from welding affected the final WP shape. Even though we incorporated a step to release this residual stress by adjusting supports of coil case before WP shape correction, some stress remained in the coil case. This is unavoidable situation which must be treated carefully by measurement and feed-back during the fabrication process.
The first TF coil was completed in January 2020 successfully. For the following coils, the gap-filling impregnation process was improved due to experience of the first TF coil and implemented on the second coil effectively. WP of the third coil was inserted in coil case and is now in welding phase. TF coil assembly process is now routinized and its adequacy is proven. The TF coil will arrive ITER site in April 2020 for acceptance tests and installation in Tokamak, showing a progress in ITER project.

[1] M. Nakahira et al., Nuclear Fusion, Vol59, No8, 086039 (2019)
[2] N. Koizumi et al., IEEE Trans. App. Superconductivity, Vol30, No4, 2971673, (2020)
[3] N. Koizumi et al., IEEE Trans. App. Superconductivity, Vol29, No5, 4200505, (2019)

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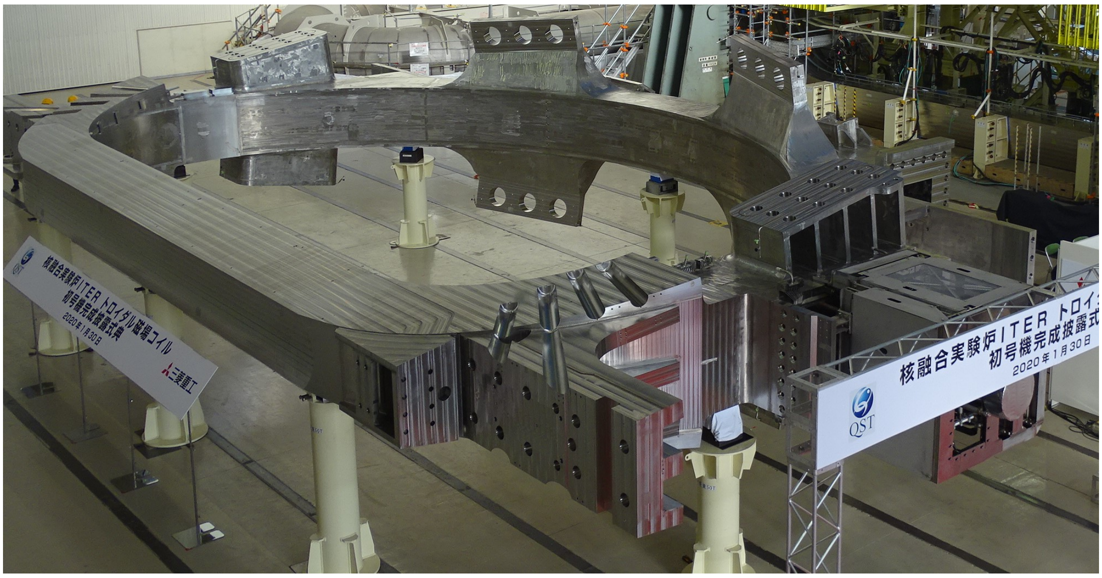

Figure 1: Completed first ITER TF Coil (at MHI, Hyogo, Jan. 2020).

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