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Fabrication of the KSTAR Toroidal Field Coil Structure

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Abstract. The KSTAR toroidal field (TF) coil structure is under fabrication upon completion of engineering design and prototype construction. The prototype TF coil structure has been fabricated within allowable tolerances. Encasing of the prototype TF coil (TF00) in the prototype structure has been carried out through major processes involving a coil encasing, an enclosing weld, a vacuum pressure impregnation, and an outer surface machining. During the enclosing weld of the TF00 coil structure, we have measured temperatures and stresses on the coil surface. Assembly test had been performed with the TF00 coil structure. We have chosen Type 316LN as material of the TF coil structure. We used the narrow-gap TIG welding method. Doosan Heavy Industries & Construction Company (DHI) will complete the fabrication of the TF coil structure in Feb. 2006.

1. Introduction

The KSTAR magnet system consists of 16 toroidal field (TF) coils, 4 pairs of central solenoid (CS) coils, and 3 pairs of outer poloidal field (PF) coils [1]. The TF coils are encased in a structure to enhance mechanical stability. The dimensions of the TF coil structure [2] are: 4.2 m in height, 3.5 m in width, and 22.5° in toroidal angle. The TF coil structure is under fabrication with completion of engineering design and prototype structure construction.

The CS coil structure [3] is supported on the top end of the TF coil structure and supplies a vertical compression of 15 MN to prevent lateral movement due to a repulsive force between the CS coils. The PF5 coil structure has a hinge-type, and the PF6 and PF7 coil structures have a flexible-type. The PF coil structures are also supported on the TF coil structure with an individual basement that is welded on the TF coil structure. The TF coil structures are supported by a gravity support that allows radial movement due to thermal contraction of the magnet system and minimizes thermal conduction from the bottom of the system by using a carbon fiber reinforced plastic (CFRP).

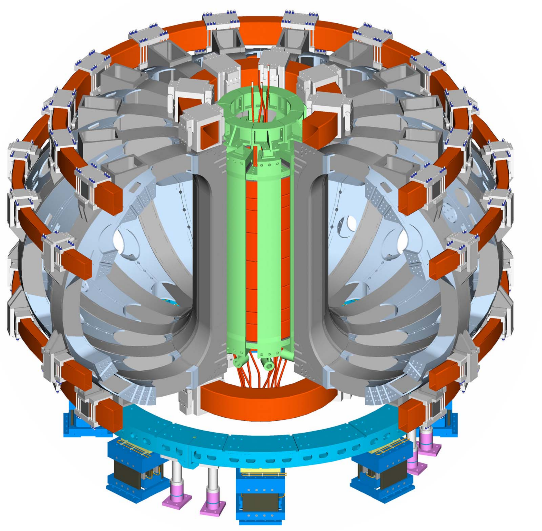


Fig.1. KSTAR Magnet System

2. Design Concept

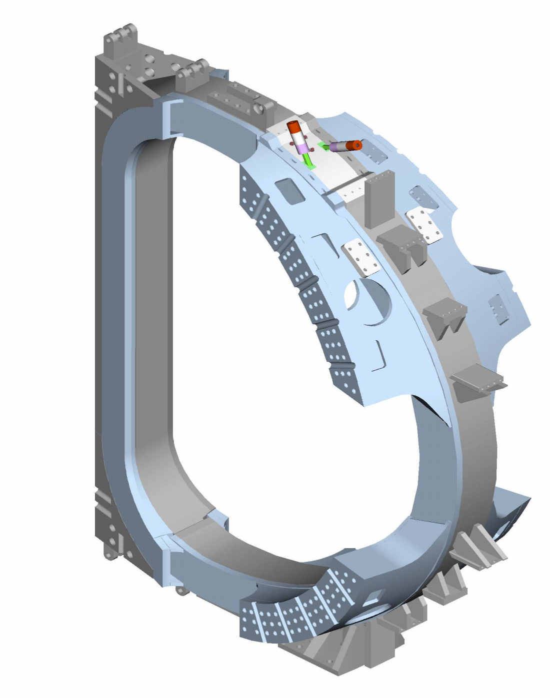


Fig.2. The TF Coil Structure (Type-III)

As shown in Fig.1, the TF coil structure has four types, because of different interface of the each structure with a vacuum vessel slanted port, a lateral support, and the CS and PF5 coil structures. Figure 2 shows the TF coil structure (Type-III). The D-shaped TF coil structures are wedged together along inboard legs to sustain an in-plane centering force. Each inner inter-coil structure (IIS) of the structure contains three shear keys and three conical bolts to provide pre-loading in toroidal direction and to resist the in-plane and out-of-plane forces which are the most critical loads on the TF magnet system [4]. Also, each outer inter-coil structure (OIS) has four (or five) shear keys and 33 (or 47) bolts according to the structure type. For absorbing accumulated fabrication and assembly errors, we have designed an adjustable spacer for the shear key and a tape ring for the conical bolt, which allows alignment of the structures during assembly. An electrical insulation is inserted into the contact surfaces between the structures in the inboard leg, the OIS, the shear keys, the conical bolts, and hexa-bolts to preclude flowing of eddy currents in toroidal direction of the structure. The thickness of the insulation is 3 mm in the inboard leg and 4 mm in the outboard leg. There are 18 cooling tubes with 8 mm outer diameter and 4 mm inner diameter embedded inside of the structure around the coil. Two cooling tubes with an outer diameter of 10 mm and inner diameter of 7 mm are attached on surface of the OIS. The coolant is supercritical helium of 4.5 K.

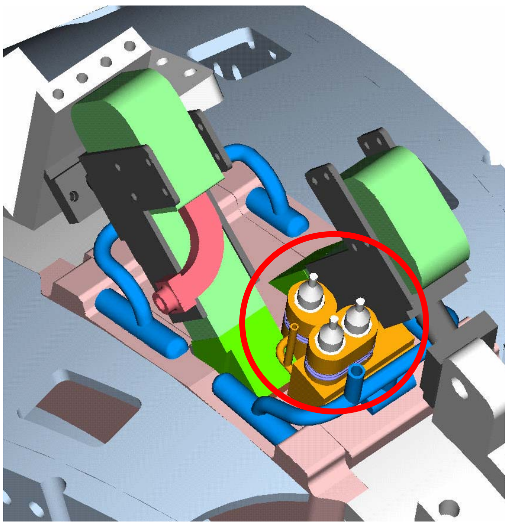


Fig.3. Three Dimensional View of Joint Box

The joint box located at the top of the structure contains the coil leads and the cooling lines of the coil and the structure. Cover plates are welded in the joint box for reinforcing the open part of the structure and supporting the coil leads. After installation of the cover plate, the structure has no clearance except periphery of the coil cooling lines. The clearance is needed to allow movement between the coil and structure. The movement generates a high stress in the coil cooling lines that is originated by the in-plane and the out of-plane forces. We have designed a guard vacuum chamber including the crevice for a vacuum isolation between inside of the structure and the cryostat as shown by a red circle in Figure 3. Major requirements of the chamber are an electrical insulation between high and low electric potential parts and prevention against the Paschen discharge from optimized helium partial pressure in the chamber. In order to meet the requirements, a transversal electrical breaker is inserted in the coil cooling lines for the electrical insulation and glass felt is filled to enhance resistance inside the chamber.

3. Fabrication

3.1 Materials

We have chosen Type 316LN for the base metal of the TF coil structure, Inconel718 for the shear key and the conical bolt, Type 316L for the cooling tube, and G10 for the insulation. The structure has mechanical design requirements as follows; 1) more than 750 MPa yield strength for the base metal and more than 90 % of the yield strength of the base metal for the weld metal at 4.5 K, 2) more than 150 MPa $m^{1/2}$ fracture toughness for the base metal and more than 130 MPa $m^{1/2}$ for the weld metal at 4.5 K. In order to verify the structural reliability, mechanical tests have been carried out for various specimens at cryogenic and room temperature by the Efremov Institute in Russia. Test standard for tensile and elastic-plastic fracture toughness is ASTM E1450-92 and ASTM E813-89, respectively. Test results are summarized in Table 1. It shows that the base and the weld metal satisfy the design requirements.

Table 1. Summary of the test results for the base and the metal of 316LN at 4.5 K

Materials	Yield strength σ_{YS}, MPa	Fracture toughness		Remarks
		J_{IC}, kJ/m^2	*K_{JC}, MPa $m^{1/2}$	
Base metal	862	139	178	
Weld metal	885	248	238	

* Converted value by J_{IC}

3.2 Fabrication Requirements

Representative allowable tolerances of the inboard leg and the outboard leg of the structure are ±1 mm and ±2 mm, respectively. A gap of 5 ~ 10 mm between the coil and the structure is needed to clear the fabrication tolerance of the coil and the structure. The location tolerance of the toroidal ring basement that stands on the gravity support is ±0.1 mm. Location and shape tolerances of the shear key hole and the conical bolt hole are ±0.1 mm and +0.03 ~ +0.07 mm, respectively. Angle tolerance for the toroidal angle of 22.5° is 0.015° that is absorbed by the insulation sheet. To reduce residual stress due to welding and machining, a vibration method is adopted. We use RT, UT, and PT as a nondestructive examination for the welded zone. Allowable permeability of the SUS316LN is 1.07 for the base and the weld metal in 200 gauss at 300 K. Allowable leak rate of the structure cooling line is 1×10^{-10} mbar l/s after 3 cycles with 30 bar for 10 minutes at 300 K.

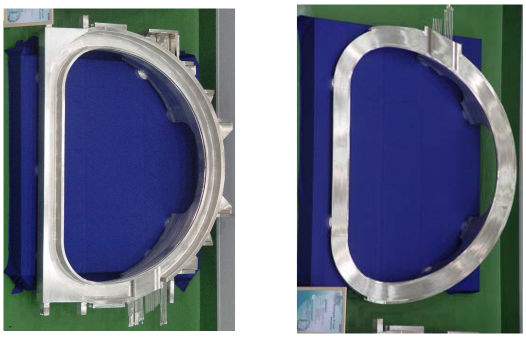
3.3 Fabrication Procedure

The fabrication procedure of the TF00 coil structure will be described as following that is major fabrication procedures.

1. Fabrication of the case and the cover structures
2. Coil Encasing
3. Enclosing Weld

4. Vacuum Pressure Impregnation (VPI)
5. Outer Surface Machining

The structure consists of the case and the cover structure that are individually fabricated. The case structure that contains the coil is c-shaped and the cover structure is a plate as shown in Figure 4. Inner surfaces of both structures are machined and the cooling tubes are embedded by welding.



(a) The Case Structure (b) The Cover Structure

Fig. 4. The TF Coil Structure

The coil is inserted inside the case structure. Figure 5 shows the process of the coil encasing. Measurements of the electrical resistance of ground insulation and a dimension of the coil were performed before the encasing. The resistance was 31.5 GΩ at 5 kV, 1 minute. We installed various thicknesses of G10 spacers in the gap between the coil and the structure for alignment of the coil to the structure through the dimensional measurement. The coil is aligned within 1 mm based on flatness, an inner wall of the inboard leg, and a top and bottom of the case structure. After the coil alignment with the spacers, the remaining space of the gap is packed with the glass felt to enhance mechanical strength of the epoxy. We have transferred coordinates of fiducial points of the coil to those of structures in order to define the axis of the structure. That axis is used as a reference during the outer surface machining. Thermocouples and strain sensors are adhered on upper surface of the coil for measuring temperature and stress that is generated during the enclosing weld. The upper gap is packed with only the glass felt that prevents high stress in the coil from welding deformation of the enclosing weld.

Fig.5. Coil Encasing with Vacuum Lifter

The enclosing weld was done with a narrow gap auto TIG welding machine as shown in Figure 6. Measured deformations in width and height of the inboard leg are 2 mm and 1.5 mm, respectively. And those in the outboard leg are 1.5 mm and 2.5 mm, respectively. The measured maximum temperature and stress on the coil surface were about 53 °C and 50 MPa, respectively. The glass felt was not burned but melted by the welding heat.

Fig.6. Enclosing Weld Process with Automatic Welding Machine

Figure 7 shows the structure on a fixture of the VPI. The gap packed with the glass felt is filled with the epoxy at the VPI process. One inlet stub with 10 mm diameter locates at a bottom of the structure, and two outlet stubs locate at the joint box. The structure was pumped down to 1×10^{-3} mbar and a leak rate was less than 1×10^{-8} mbar l/s. A Room Temperature

Vulcanizing that is eliminated after the VPI seals the clearance around the cooling lines. GY282/HY918 has been chosen as the resin and hardener for the epoxy, which is the same as the coil insulation. 70 liters of the epoxy is filled for 12 hours at 40 °C. Curing of the epoxy was done at 90 °C for 8 hours and at 120 °C for the next 15 hours. The resistance of the coil ground insulation after the VPI was 102 GΩ at 1 kV, 1 minute.

Fig.7. Vacuum Pressure Impregnation

We machined the outer surface of the structure with a Plano Miller as shown in Figure 8. The workable capacity of the machine is a length of 21 m, a width of 6 m, and a height of 5.5 m. Accuracy of the machine is 0.04 mm / 1000 mm. Flatness and an angle tolerance of the structure after the machining are 0.3 mm and 0.01°, respectively.

Fig.8. Outer Surface Machining

4. Assembly

The KSTAR assembly was launched in early 2004. The TF coil structure is inserted through 22.5° opening of the vacuum vessel and rotated coaxially to the vacuum vessel in toroidal direction up to the proper location. An assembly jig for the structure had been fabricated and installed in the KSTAR experimental hall in May 2004. The performance test of the assembly jig had been successfully done with the TF00 coil structure as shown in Figure 9 [5].

The first TF coil structure will be assembled in January 2005. And the last structure will be assembled in February 2006. Delivery interval of each structure is about four weeks. The insulation will be attached on the side surface of the inboard and the outboard legs, the shear key holes, and the conical bolt holes at the KSTAR experimental hall. The insulation thickness of the inboard and the outboard legs between two adjacent structures will be decided after position measurement of the designated location. A misalignment of the shear key holes and the conical bolt holes will be measured and compensated by the spacers and the taper rings, respectively.

Fig.9. Assembly Test

5. Conclusions

The TF00 coil structure were successfully fabricated through procedures of the coil encasing, the enclosing weld, the VPI, and the outer surface machining. The flatness and the angle tolerance of the TF00 coil structure are 0.3 mm and 0.01°, respectively. Assembly test of the TF00 coil structure was performed. Doosan Heavy Industry & Construction Co started the fabrication of the 16 TF coil structures in January 2004. Present progress of the fabrication is about 20 %. The first TF structure will be completed and assembled in January 2005 and the last one in February 2006.

Acknowledgement

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