A Study on the Welding Technology for the Fabrication of Korean Fusion Reactor(KSTAR)

Dae-Soon KIM, Chang-Ho Choi*
Hyundai Heavy Industries Co. Ltd, Ulsan Korea, drkim@hhi.co.kr
*Korea Basic Science Institute, Daejeon Korea, chchoi@kbsi.re.kr

ABSTRACT

Korean Fusion Reactor(KSTAR) system consists of a vacuum vessel, in-vessel components, cryostat, thermal shield, super-conducting magnets and magnet supporting structures. These systems are in the final stage of engineering design with the involvement of industrial manufacturers. The overall configuration and the detailed dimensions of the KSTAR structure have been determined and the first stage of manufacturing is progressing now.

In this study, the fabrication and assembly sequence were evaluated in viewpoint of high strengthening joints and very high accuracy. Especially for this purpose, the special cleaning process and welding process were proposed for high strengthening austenitic stainless steel which shall be used at cryogenic temperature. The draft procedure qualification data for welding process are presented with precise welding data including special narrow groove design. For the cooling line attachment on the surface of inside wall of magnet structure case, Induction brazing technology is introduced with some special jigging system and some consumables.

Keywords
HS-TIG Welding, Strengthened Stainless Steel, Welding deformation, Induction Brazing

1. INTRODUCTION

THE mission of the Korea Superconducting Tokamak Advanced Research (KSTAR) Project is to develop a steady-state-capable advanced superconducting tokamak, and to establish a scientific and technological basis for an attractive fusion reactor [1]. Fully superconducting magnets and long-pulse operation capability are introduced to meet the mission and research objectives of KSTAR.

The major parameters of the tokamak are: major radius 1.8 m, minor radius 0.5 m, toroidal field 3.5 Tesla, and plasma current 2 MA with a strongly shaped plasma cross-section and double-null divertor [2]. The main components of the KSTAR tokamak are a vacuum vessel, a cryostat, and the magnet system, which consists of toroidal field (TF), central solenoid (CS), and poloidal field (PF) magnets as shown in Fig. 1. The TF coil structures enclose the superconducting TF coils to protect the cable-in-conduit conductor (CICC) from mechanical, electrical, and thermal loads. The TF coil structures, which are the main structural components in the KSTAR magnet system, support three pairs of PF coils as well as four pairs of CS coils. All of the superconducting coils are located in the cryostat. The CS assembly (stack of PF1 to PF4 coils) is attached to the top of the TF case. The PF coils are arranged symmetrically with respect to the equatorial plane.

TF Coil Case

The TF winding packs are enclosed in welded cases made of plates and blocks. The basic material of

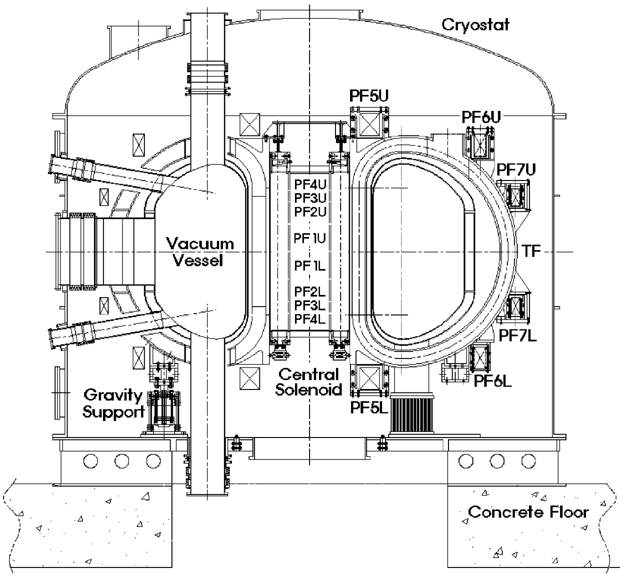


Fig. 1. Configuration of the KSTAR tokamak.

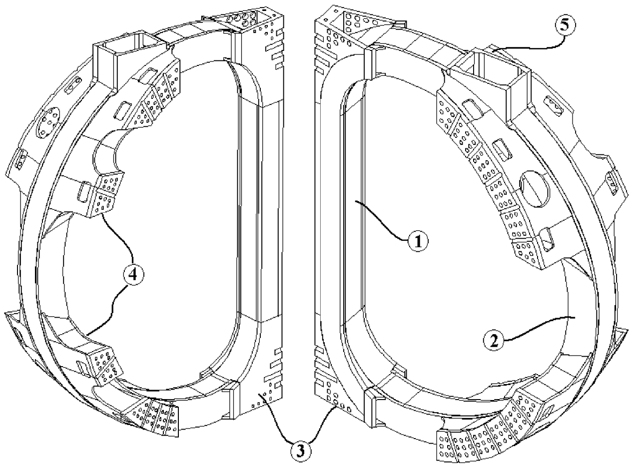
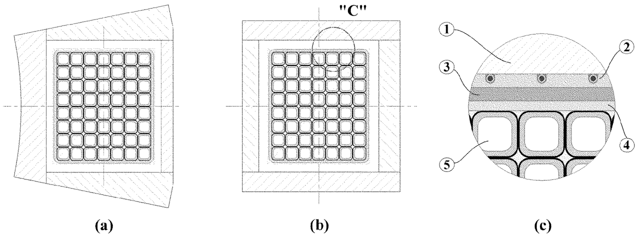


Fig. 2. Isometric views of TF Coil structure.
① Inboard leg, ② Outboard leg,
③ Inner ICS, ④ Outer ICS, ⑤ Joint box.

structures is a strengthened stainless steel, JJ1, which is proposed for the ITER TF structure [3]. The segmentation scheme of the TF structures is revised from an octant system to 16 segments in order to reduce the eddy current heating at the inboard leg as well as at the outer inter-coil structures.

The cross-sections of the inboard legs are “keystone” shaped but the outboard legs have a rectangular cross-section as shown in Fig. 3. The cases are wedged along the inboard straight leg to sustain the in-plane centering Lorentz forces. The TF case contains cover-plate-type cooling channels and epoxy filler as well as winding pack.



(a) (b) (c)

Fig. 3. Cross-sections of TF case. (a) Inboard leg, (b) Outboard leg, (c) Detail of cooling channel and winding pack. ① TF Case, ② Cooling tubes and cover plate, ③ Filler, ④ Ground insulation, ⑤ CICC and turn insulation.

The cooling tubes are brazed by induction heating to the inner surfaces of the TF case. This cooling channel has been designed to ensure structural and thermal stability. The brazing techniques related to the cover-plate-type cooling scheme have been studied by HHI.

INTER-COIL STRUCTURES

The inter-coil structures (ICS) are strongly connected to the TF cases, so that the TF magnet structure can be robust as shown in Fig 2. The ICS contains shear keys and bolts to provide pre-loading in toroidal direction and to resist in-plane and out-of-plane (OOP) forces, which are the most critical loads on the TF magnet system. The double plates of the outer ICS are curved only in vertical direction, so that the plates can be easily shaped by bending. The outer ICS shape was designed to reduce the stress concentration at the connection near the equatorial plane.

Adjustable conical bolts are adopted to support both shear and tensile forces at the inner ICS simultaneously, and the design of these bolts is based on the design of ITER FEAT [4]. The conical bolts and shear keys are specially designed for easier assembly and flexibility to provide good alignment with accommodation for cumulative manufacturing tolerances. Electrical insulation sheets are inserted at the contact surfaces of the inboard leg and ICS including bolts, keys, and keyways to minimize eddy currents flowing around the structure.

GRAVITY SUPPORT

The magnet system is mounted to the gravity support, which consists of a stiff toroidal ring, eight supporting posts and eight vertical limiters for redundancy in emergency. The supporting posts are mainly made of stainless steel 316 LN and carbon-fiber-reinforced plastic (CFRP) material which has low thermal conductivity and high strength at cryogenic temperature. It is flexible in radial direction so as to absorb the thermal shrinkage of the TF coil structure and it should also be rigid enough to support the magnet weight and the lateral loads such as plasma disruption loads and seismic loads. The ring and post are cooled by 4.5 K supercritical helium and 80 K gaseous helium, respectively.

A full scale model of the supporting post was manufactured and used to demonstrate the fabricability and the structural reliability. Tests under static and cyclic loads were performed at room temperature and low temperature. The test results showed that the post was fabricable and structurally reliable [5].

INTERFACE STRUCTURES AND OTHER COMPONENTS

The TF structure interfaces with the gravity support, the CS structure, the PF coil supports and vacuum vessel through the lateral support. The CS magnet assembly is mounted at the top end of the TF coil structure. The CS support structure is a toroidally insulated ring with eight lugs which are bolted on the top surface just above the inboard straight legs of every other TF Coil case [6]. PF 5U and 5L coils are connected respectively to the top and bottom surfaces just above the inboard straight legs of every other TF coil case. Each of PF 6U, 6L, 7U, and 7L coils is attached at 16 places to the TF coil cases. The PF coil supports allow the PF coils to move relative to the TF structure in radial direction using links and pivots. The joint box located at the top of the coil contains the TF coil leads, the inlets and outlets of the case cooling lines, and the cooling connections to the TF coil conduit at the low field side of the TF coil. The joint box should be made of thick plates to reinforce the opening zone of the TF case.

2. MANUFACTURING AND WELDING TECHNOLOGY DEVELOPMENT

The overall TF coil structure is assembled with 16 welded modules through bolted connections. The basic module of the TF structure has two subassembly weldments, a case and a cover. Each of these subassemblies contains the parts fabricated by bending and machining of rolled plates and forged blocks. A number of welding and alignment fixtures are required in all stages of fabrication to ensure that the TF coil modules fit together properly and to match them with other components at the time of final assembly. The structure welding can be subdivided into two basic types: subassembly welds and closure welds. Most of the welds are full penetration welding that will be done at the subassembly stage in order to have better access to weld joints, to make handling of parts easier and to maintain dimensional control of the overall assembly. The inside surfaces of the subassembly weldment of the TF coil case combined with full ICS have to be accurately machined to correct the deformation due to welding distortion. The cooling tubes and cover plates are attached on the inside of cases by brazing. The circumferential closure welds will be done from one side only after installing the winding pack inside the case with shims. Great care will be required to avoid over-heating of the epoxy insulation and the brazing part of the cooling pads. A gaseous purge of the coil-to-case filler space and cooling tubes of the TF case will be used to cool off the coil. After the final VPI operation to fill the coil-to-case space, the following critical interfaces will be machined to the final dimensions required for installation in the tokamak.

WELDING TECHNOLOGY

EXPERIMENTAL PROCEDURE

The JJ1 material to be developed for the magnet structure steel is a kind of austenitic stainless steel, but adapts quite different alloy design from those of the ordinary 3xx series of austenitic stainless steels as shown in table 1. In terms of mechanical properties, the material also needs an excellent fracture toughness (KIC) > 200Mpa√ m and yield strength > 1,000Mpa of which it can be endured at 4K of operating temperature.

One test coupon made up of JJ1 forging and rolled plate, was prepared in order to evaluate the integrity of welded joint and to find practical welding problems in advance. Table 2 shows the actual strength and hardness of materials, and the fit-up condition of test coupon was shown in figure 4. The welding process used to weld the test coupon was GTA welding process and the heat input was limited to be 15kJ/cm maximum. The cross-section of weld and the deposit sequences are as shown in figure 5, which can be found that the 67 passes of GTA welds were deposited for the 35mm thick welded joint. A various tests (NDE, tensile, observation of microstructure) were performed for the completed test coupon weld

Table 1. chemical composition of JJ1 material

	Chemical composition (wt%)									
	C	Si	Mn	P	S	Ni	Cr	Mo	Co	N
Rolled plate	0.014	0.55	9.84	0.024	0.002	11.72	11.98	4.76	0.14	0.239
Forged block	0.013	0.53	9.78	0.025	0.002	11.69	11.93	4.76	0.14	0.235

Table 2. strength and other mechanical properties

	Yield strength (MPa)	Tensile Strength (MPa)	Hardness (HB)
Forging	359	672	-
Rolled plate	344	689	182
Requirement	min. 286	min. 626	max. 217

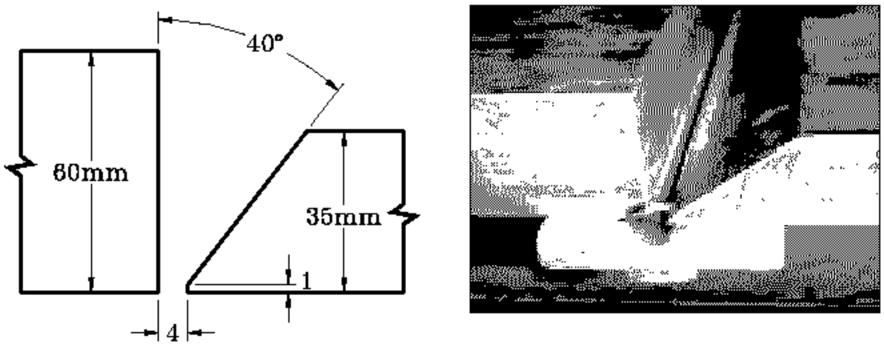


Fig. 4. fit-up condition & test coupon fit-up

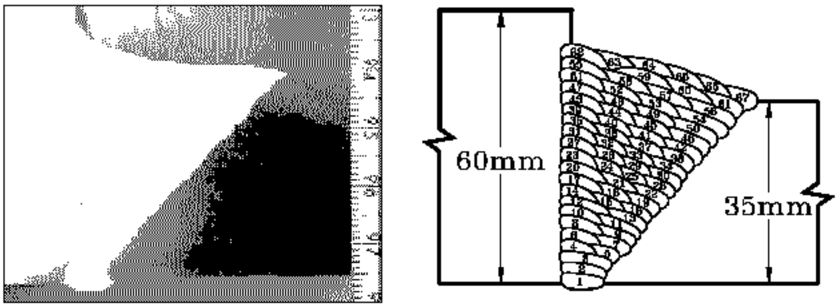
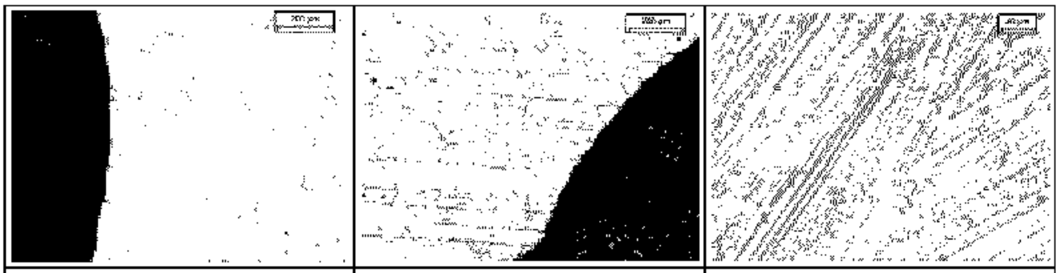


Fig. 5 . cross-section of test weld & weld sequence

TEST RESULTS

Two kinds of nondestructive examinations (radiographic & dye penetration examination) were preformed for the test coupon weld, and no weld defects were found. Actually, even though the weld had high possibility of hot cracking due to the micro-structural characteristic of weld, the NDE test results confirmed that the weld had enough resistance to hot cracking by controlling the impurities such as sulfur or Phosphorus. The figure 6 shows the microstructure of HAZ where Cr-carbide is precipitated in the grain boundary and the full austenitic structure weld without trace ferrite.

The mechanical tests including tensile, bend and hardness tests were preformed. In figure 7, the tensile specimens were fractured at the weld, which coincided with hardness test results showing lower hardness value in the weld (weld : 164 ~ 184 & HAZ : 207 ~ 236), and the weld strength was 14MPa higher than 626MPa of minimum strength required for the JJ1 material. Moreover, the bend test results (4t x 180^{O}) also were satisfied because no crack were found in the bend specimens shown in figure 8, which means that weld has a good ductility (around 20% of elongation).



HAZ (forging) | HAZ (rolled plate) | weld metal

Fig. 6 . microstructure of weld and heat affected zone

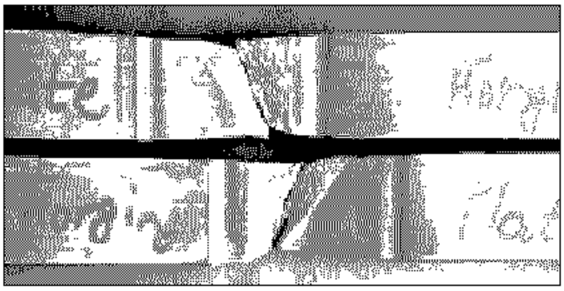


Fig. 7 . tensile test specimens fractured at weld

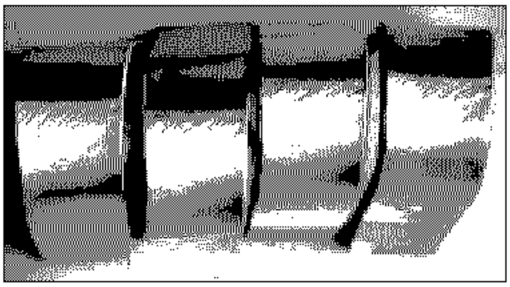


Fig. 8 . bend test specimen bent (180°)

The welding deformation of toroidal field (TF) coil structure has been simulated with simplified thermo-elastic FEM analysis. The parameters for the analysis are defined from test result of welding with mock up part. The welded parts are modeled as a shell element with layers in the thickness direction for application of different temperature between top and bottom surface to simulate angular distortion. The welding test of mock up with simplified geometry but having shape or thickness analogous to parts constituting real TF coil structure has been performed to evaluate the welding shrinkage at constraint condition. Method of welding is narrow groove TIG with hot wire switching (HS) technique. The welding conditions used for the test are shown in Table 3. Figure 9 shows the schematization of the mock up and measured positions for the welding shrinkage. Figure 10 shows measured shrinkage from center to lateral end point of top and bottom surface under constraint with tack weld. The final shrinkage of the top and bottom surface at 17th layer is respectively 4.42 mm and 1.86 mm. The angular distortion is assumed as difference of welding shrinkage in the thickness direction.

Table 3. HS TIG welding conditions of JJ1

JJ1	
Item	Condition
Filler Wire	ϕ 1.2 mm
Current	max. 330 A
Voltage	10.5 ~ 11.5 V
Speed	100 ~ 150 mm/min

The TF coil structure consists of inboard leg, outboard leg and forged parts. Figure 11 shows the deformed shape of outboard leg at a constraint removal after welding. The calculated results represent relatively large welding deformation. So, as consequence of the results obtained, welding fixture and pre-deformation technique are still in progress to reduce the welding deformation.

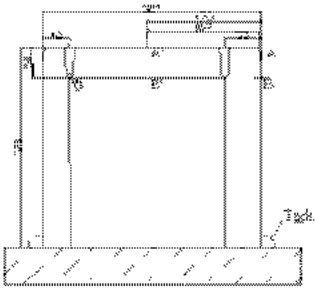


Fig. 9. Schematic diagram of mock up part

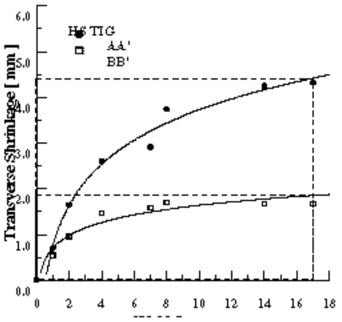


Fig. 10. Results of welding shrinkage

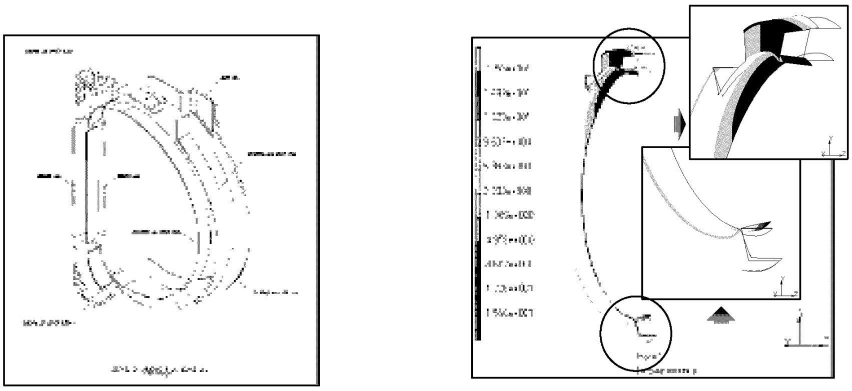


Fig. 11. TF coil structure and deformed shape of outboard leg

3. CONCLUSIONS

The engineering design of the KSTAR magnet system is in the final stage and Mmanufacturing work is starting now. In this study the manufacturing process is proposed in viewing from keeping of very precise dimension with suitable welding technique including brazing technique to attach the cooling pipes in the case structure. More manufacturing technologies will be developed and tested with the manufacture of a prototype of the TF coil structure.

REFERENCES

[1] G. S. Lee et al., "The design of the KSTAR tokamak," *Fusion Engineering and Design*, vol. 46, pp. 405-411, Apr. 1999.

[2] Y. K. Oh et al., "KSTAR magnet structure design," *IEEE Trans. Applied Superconductivity*, vol. 11, pp. 2066-2069, March 2001.

[3] F. Wong and N. Mitchell, "Selection of tokamak toroidal field coil case structural materials," *Advances in Cryogenic Engineering (Materials)*, Vol. 44, pp 65-72, 1998.