Development of CICC for KSTAR Superconducting Magnet System

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***Abstract*—The KSTAR (Korea Superconducting Tokamak Advanced Research) superconducting magnet system adopts a superconducting CICC(Cable-In-Conduit Conductor) type conductor. It consists of 16 TF (Toroidal Field) coils and 14 PF (Poroidal Field) coils and it also uses two different types of CICCs-Nb_3Sn cable with Incoloy 908 conduit and NbTi cable with 316LN stainless-steel conduit. A special CICC jacketing system is developed for the KSTAR CICC fabrication: the tube-mill process, which consists of forming, welding, sizing and squaring procedure. The cabling process for TF and PF superconducting cable and the fabrication process of each CICCs (TF CICC and PF CICC) is described. The welding of conduit materials are also discussed. The fabrication results such as the geometrical specification, micro structure and the void fraction will be discussed.**

***Index Terms*—CICC, jacketing, KSTAR, PF coil, superconducting cable, TF coil.**

I. Introduction

The GOAL of KSTAR project is to develop a steady state advanced superconducting tokamak for an attractive fusion reactor. To achieve this goal, the superconducting coil is used for the magnet system. The KSTAR magnet system consists of the TF magnet system and the PF magnet system [1].

The KSTAR TF magnet system is fully superconducting and consists of 16 TF coils. The TF coil system provides a field of 3.5 T at a plasma center, with a peak field on the TF coils of 7.5 T. The stored energy is 470 MJ. TF coils use a Nb_3Sn CICC with a Incoloy alloy 908 (afterward, Incoloy 908) conduit. The Nb_3Sn strand has KSTAR HP-III specifications in which the critical current density is greater than 750 A/mm^2 at 12 T, 4.2 K and the hysteresis loss is less than 250 mJ/cm^3 for field variation between $+3$ T and -3 T at 4.2 K. The total mass of Nb_3Sn for TF coil fabrication is 15.7 ton. The cable pattern is $3 \times 3 \times 3 \times 3 \times 6$ and includes 486 strands. The nominal current of the TF coils is 35.2 kA and all coils are connected in series. Each coil is continuously wound without joint [1].

The KSTAR PF magnet system consists of 8 coils in the CS (Central Solenoid) coil system and 6 outer PF coils (PF 5-7). It uses internally cooled superconductors. CS and PF 5-7 coils can provide 17 V s and can sustain the plasma current at a length of 2 MA for 20 s inductively. The CS (PF 1-4) and PF 5 coils use Nb_3Sn strands which has KSTAR HP-III specification. The PF 6-7 coils use NbTi strands in which the critical current density is greater than 2700 A/mm^2 at 5 T, 4.2 K and the hysteresis loss is less than 200 mJ/cm^3 at field variation between $+3$ T and -3 T at 4.2 K. The cable pattern of PF coils is $3 \times 4 \times 5 \times 6$. The total mass of Nb_3Sn strands for PF 1-5 coils is 7.7 ton and the total mass of NbTi strands for PF 6-7 coils is 9.4 ton.

CICCs for TF and PF are fabricated using tube mill process. Incoloy 908 is used as conduit materials for TF and PF 1-5 CICC. Stainless steel 316LN is used as conduit materials for PF 6-7 CICC. This paper focuses on the fabrication procedure of conductor and the fabrication results.

TABLE I
TF and PF Conductor Parameters

Parameters	Units	TF	PF1-5	PF6-7
Superconducting material		Nb3Sn	Nb3Sn	NbTi
Strand diameter	mm	0.78±0.01	0.78±0.01	0.78±0.01
Jc at 4.2K	A/mm^2	>750(@12T)	>750(@12T)	>2700(@5T)
n-value		>20	>20	>25
AC loss (±3 T)	mJ/cm^3	<250	<250	<200
RRR		>100	>100	>100
Cu/Non-Cu		1.5±0.15	1.5±0.15	2.8±0.28
N_{strand}		486	320	320
Conduit size	mm	25.65	22.3	22.3
Conduit thickness	mm	2.86	2.41	2.41
$A_{conduit}$	mm^2	244.6	175.6	175.6
$A_{non\text{-}Cu}$	mm^2	61.9	45.9	30.2
A_{Cu}	mm^2	170.3	126.1	141.8
A_{Helium}	mm^2	142.6	112.1	112.1
Void Fraction	%	36.5	37.5	37.5

II. Material Preparation

A. Cabling

TF and PF 1-5 coils use a Nb_3Sn strand and PF 6-7 use NbTi strand. MELCO (Mitsubishi Electric Corporation) and OAS (Otokumpu Advanced Superconductor) supply the KSTAR Nb_3Sn strands and OAS supplies the KSTAR NbTi strands. All strands are chrome plated with the thickness of 1 ± 0.2 μm.

The cable patterns of TF and PF conductors are respectively $[(2 + 1\text{Cu}) \times 3 \times 3 \times 3 \times 6 + 7\text{Cu}]$ and includes 486 strands, and $[(2 + 1\text{Cu}) \times 4 \times 5 \times 6 + 7\text{Cu}]$ and includes 360 strands. The main conductor parameters are summarized in Table I [2].

The first stage of every cable is a triplet which is composed of one OFHC (Oxygen Free High Conductivity) copper strand and two superconducting strands.

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TABLE II
THE CICC FABRICATION PROCEDURE (UNIT: mm)

Tube mill procedures	TF CICC	PF CICC
Strip	2.86(Thickness) × 94.54(Width)	2.41 Thickness × 82.1 Width
Welding	out.: 31.85 Inner dia.: 26.25	Outer dia.: 27.6 Inner dia.: 22.6
Sizing (4% reduction)	Outer dia.: 29.3 Inner dia.: 23.7	Outer dia.: 26.5 Inner dia.: 21.5
Squaring (CICC conduit size)	Outer sqr.: 25.6 × 25.6 × 2.86T Inner sqr.:19.8 ×19.8	Outer sqr.: 22.3 × 22.3 × 2.41T Inner sqr.:17.3 ×17.3

The cable twist pitches of TF and PF cable multiplets are respectively 40-80-160-240-360 mm and 40-80-145-237 mm. At the final stage of cable fabrication, dummy OFHC (0.78 mm× 7 strands) are inserted at the center of cable to fit the void fraction and the cable is formed to final size using forming roll. The cable is wrapped with the thin stainless-steel strip, 30 mm wide and 0.05 mm thick, with 20% overlap at each side [2]. The final diameter of TF and PF cables with stainless steel wrapping are 22.3 mm and 20.3 mm.

B. Jacketing Preparation

The critical current density of Nb_3Sn superconducting strand is reduced by mechanical strain. If the thermal expansion coefficient of the conduit material is the same as the one of Nb_3Sn strand, no strain occurs during the cool down of magnets using Nb_3Sn CICC and the current density is not degraded. Incoloy 908 is used as the conduit materials for TF and PF 1-5 CICC and designed to match the thermal expansion coefficient of Nb_3Sn strand [3]. It is a nickel-ferrous alloy and the general micro-structure of Incoloy 908 is a single phase austenitic structure. The strengthening is achieved by precipitation of $\Upsilon'[Ni_3(Al, Ti, Nb)]$ during the Nb_3Sn superconductor reaction [4].

Stainless steel 316LN is used as the conduit materials for PF 6-7 CICC. The STS 316LN belongs to the austenitic family of stainless steels which are noted for their corrosion resistance and high tensile strength [4].

The tube mill process is used for the fabrication of CICC. The manufacture parameters, related to forming, welding, sizing and squaring procedure, are summarized in Table II.

III. CICC FABRICATION PROCEDURE

A. Strip Joint

The coil of jacketing strip is supplied by the length of 100∼120 m/coil and the strip must be joined by welding to provide enough length of CICC. In case of Incoloy 908 weld joint becomes hardened after welding by precipitation. During the tube mill process the strip experiences a strong force, so the hardened part should not be produced [3]. Water quenching of the weld joint is performed as a post heat treatment to reduce the difference in mechanical properties between the welded zone and the base metal. It helps to prevent from the forming of the Υ' precipitation after welding. The Vickers hardness test result shows that the hardness of weld, heat affected zone, and base metal are similar (205∼210 Hv). To determine the strip joint angle, tensile test has been performed at various joint angle. The mechanical properties of 45 degree joint is superior to other joints and the strip joint is prepared by 45 degree [4]. Strip joint parts are welded by automatic GTAW(Gas Tungsten Arc Welding). After the strip joint welding, post-heat treatment, weld joint machining, strip cleaning, and strip rewinding to a strip pay-off device are performed in turn.

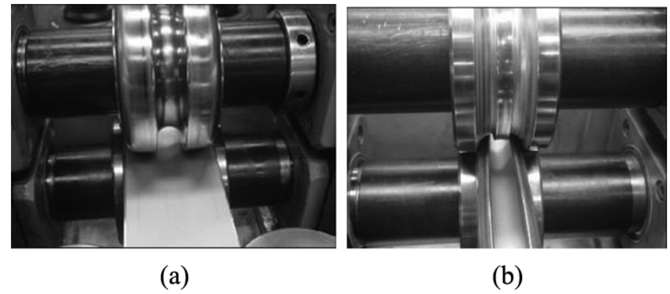


Fig. 1. The breaker pass and fin pass for tube forming. (a) Breaker pass; (b) fin pass.

B. Forming

A forming stand forms the strip to the tube of nominal size through a series of progressive roller dies. The cable is introduced on top of the strip by the cable payout equipment. The strip enters the four forming passes. The first pass is breaker pass. It is designed to shape the edge of the tube. The next three passes form the strip to circular shape progressively. The cable is put in the forming tube and it passes through each grooved forming roll. The idle roll is used between forming pass to prevent tube rotation. After the four forming pass, tube forming continues in a series of finned passes. The purpose of the fins is to prevent the strip from rotating around the center axis and to locate the strip in the right pass. The breaker pass and fin pass are shown in Fig. 1. After fin pass, the tube formed into circular shape and then it passes into the weld box.

C. Welding

Circular shaped tube passes into the weld box with three pairs of adjustable side rolls for jacket welding. The weld seam is maintained on top of the tube. The weld station is the most critical part in the CICC fabrication procedure. The weld station is shown in Fig. 2. The GTAW is used for the welding because GTAW is widely used for nickel alloys and the production of a similar product. The recommended shielding gas for CICC welding is $He, Ar, Ar + He, Ar + H_2$. He gas can enhance welding but electrode life time becomes shorter and stability is not better than Ar or $Ar + H_2$ (below 5%). The arc voltage for a given arc length is much greater with $Ar + H_2$ than Ar, so the heat input of $Ar + H_2$ is greater than Ar. Consequently $Ar + H_2$ (below 5%) is used for CICC welding since small amounts (below 5%) of hydrogen addition can produces hotter and more uniform bead surfaces. The flow rate of shield gas with 10∼12 l/min gives the uniform welding bead. The purity of Ar and He is critical for preventing welding defects. The

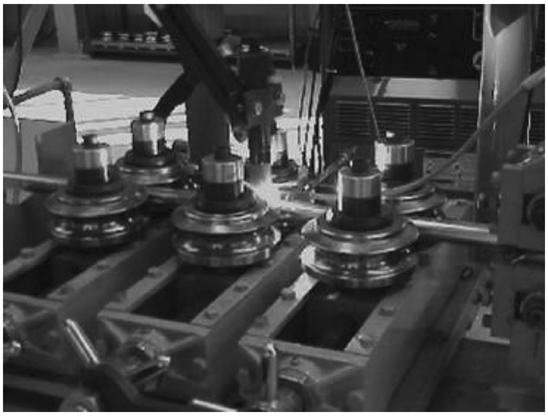


Fig. 2. Weld station for CICC welding.

torch is held at nearly 90 degrees to the tube because an inclined torch can cause aspiration of air into the shielding gas. The arc length is key parameter for Ni-alloy welding. To ensure a sound weld, the arc length is maintained as short as possible. The maximum arc length is 1.27 mm and the optimum arc length is 0.5~0.8mm [5].

Welding part is quenched by water after the welding to minimize the hardening of weld and to reduce the probability of cable damaging due to weld heat. The face-bead of weld is removed using a bead grinder giving a correct appearance after sizing and squaring process because thickness of the weld part becomes thicker after welding. An eddy current test device is used as a non destructive test of jacket weld after bead grinding. After the welding process, the tube diameter for TF and PF CICC are respectively 31.9 mm and 27.6 mm.

D. Sizing and Squaring

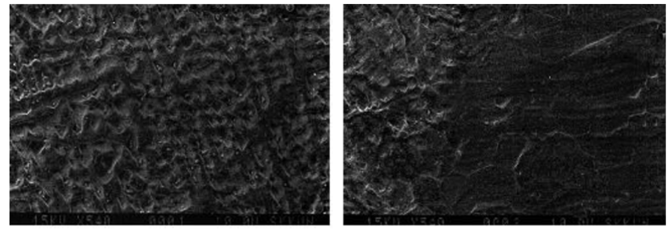
The sizing stand consists of 8 pairs of driven vertical rolls and 8 pairs of idler side rolls. It can transfer the tube and reduce the diameter of the tube progressively. After sizing process, the tube diameter is reduced to the scheduled diameter. In case of TF CICC, the sizing stand reduces the tube diameter from 31.9mm to 30.6 mm and in case of PF CICC, the sizing stand reduces the tube diameter from 27.6 mm to 26.5 mm.

After the reduction of the tube size, a squaring station is used to form the final shape of the CICC.

Cabling and jacketing were performed at Nexans Korea, one of the famous cable company in Korea.

IV. Discussion

A LASER measurement device is used continuously to check the final size of CICC. Both width and height of the TF CICC were 25.65 ± 0.05 mm and those of the PF CICC were 22.3 ± 0.05 mm. The thickness of TF jacket and PF jacket is respectively 2.86 ± 0.05 mm and 2.41 ± 0.05 mm which are in agreement with the specifications. The height of the bead can be managed below 1 mm and the welding back bead seems not to damage the superconducting cable because the cable is examined by CICC jacket removing after jacketing. The microstructure of Incoloy 908 weld and heat affected zone (HAZ) are shown in Fig. 3. The weld shows a typical cellular-dendritic microstructure. The grain size within the weld zone is actually



(a) (b)

Fig. 3. The microstructure of Incoloy 908 weld (a) and heat affected zone (b).

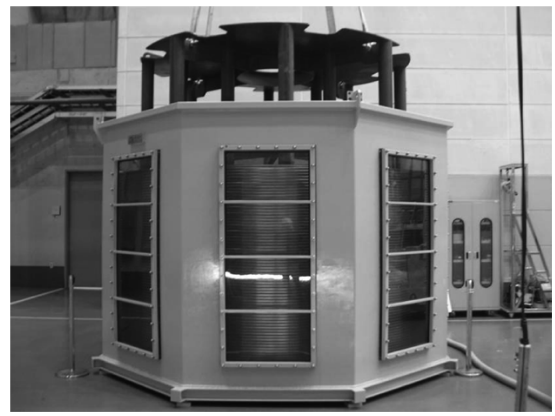


Fig. 4. Water chamber for the CICC leak check.

smaller than that of the heat affected zone. Porosity and crack is not found both in the weld and the HAZ (Heat Affected Zone). The void fraction of the CICC is measured both by calculation and Archimedes' principle. Each jacket size is measured and cable volume in unit length is calculated to calculate the void fraction. And each jacket volume and cable volume is measured to adopt the Archimedes' principle. The average results of calculation and Archimedes principle for TF CICCs were respectively 34.4% and 32.5%.

After jacketing, the CICC is pressurized with helium at 50 atm and the leak check is performed in the water chamber as shown in Fig. 4. Bubble is generated in the water chamber if there is leak in the CICC. 10~20 leak points are discovered after leak check of each 640 m TF coil. The average porosity size is below the diameter of 100 μm.

A machining device is developed to grind the repairing part because the area to be repaired should be prepared for welding by machining. It can move along CICC spool and can make the groove for repairing around the leak point. The repair welding is performed sequentially on the repaired part after the leak checking. The repair welding is performed by GTAW. High purity helium atmosphere (more than 99%) is required inside of the CICC during the welding. After the welding, the weld is grinded as a surface finishing treatment [5]. The repair process is performed until leak is not detected. 10~20 operations are performed after leak check of each 640 m TF coil.

The overall TF CICC including TF prototype (640 m) and TF01-17(640 m × 17) are fabricated. CICCs for back ground magnetic field generation system coils (920 m× 2), PF3 (290 m× 2), PF4 (440 m × 2), PF6 (1300 m × 4) and PF7 (1700 m× 2) coils are fabricated. CICCs for

PF1 (670 m$\times$ 2), PF2 (550 m $\times$ 2) and PF5 (1430 m$\times$ 2) will be fabricated by February 2006.

V. Conclusion

The KSTAR CICC was fabricated by tube mill process. The shape, weld, microstructure and void fraction of the CICC were sufficiently satisfied with the requirement (30$\sim$35%).

The CICC repair process and leak detecting process were also developed because CICC leak was occurred. The repair process and the leak detecting process were applied for other TF and PF CICC. It could overcome CICC welding defects.

Consequently, The KSTAR CICC fabrication process will serve as a good reference for world fusion community.

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