Development of CICC for KSTAR TF Coil System

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***Abstract*—The KSTAR (Korea Superconducting Tokamak Advanced Research) superconducting magnet system consist of 16 TF's (Toroidal Field) and 14 PF's (Poloidal Field) coils. Internally-cooled cabled superconductors will be used for the magnet system. The magnet systems adopt a superconducting CICC (Cable-In-Conduit Conductor) type conductor. The KSTAR TF CICC uses Nb_3Sn Superconducting cable with Incoloy 908 conduit. For the fabrication of TF 1∼3 CICC, cables have been fabricated and the cable has the length of 640 m and the diameter of 22.3 mm. A continuous CICC jacketing system is developed for the CICC jacketing and the jacketing system uses the tube-mill process, which consists of forming, welding, sizing and squaring procedures. The cabling and the jacketing process is described. The welding condition of the Incoloy 908 and design specification of CICC's are also discussed. The fabrication results including the geometrical specification and the void fraction will be discussed.**

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

I. Introduction

THE KSTAR reactor is a tokamak with a central field of 3.5 T at the major radius of 1.8 m. The magnet system of the device is a fully superconducting magnet system which consists of 16 TF coils and 14 PF coils. Both the TF and PF coil systems use internally cooled superconductors.

The TF coil system provides a field of 3.5 T at a plasma center, with a peak flux density at the TF coils of 7.5 T. The stored energy is 470 MJ [1]. Incoloy alloy 908 (afterward, Incoloy 908) conduit and Nb_3Sn superconducting cable are used for the TF CICC. The Nb_3Sn strand has KSTAR HP-III specifications in which the critical current density is more than 750 A/mm^2 at 12 T, 4.2 K and the hysteresis loss is less than 250 mJ/cc per ± 3 T. The cable pattern is $3 \times 3 \times 3 \times 3 \times 6$ of 486 strands. The nominal current of the TF coils is 35.2 kA with all coils in series. Each coil is continuously wound without joint.

The PF coil system provides 13.6 V-sec and sustains the plasma current of 2 MA for 20 seconds inductively which consists of 8 coils in the CS(Central Solenoid) coil system and 6 outer PF coils. The PF 6–7 coils use NbTi CICC with a modified stainless steel 316LN(STS 316LN+), while the other PF coils use Nb_3Sn in an Incoloy 908 conduit.

In order to fabricate the TF CICC, cabling and jacketing procedure were confirmed. Three TF CICC's of 640 m in length have been fabricated for the TF 1∼3 coils. This paper is focused on the cabling and jacketing of KSTAR TF CICC and the fabrication result is discussed.

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TABLE I
ELECTRICAL PROPERTIES OF Nb_3Sn STRAND FOR KSTAR

Strand Type	Jc (A/mm2)	Qh (mJ/cc)	RRR
MELCO Type A	995	164	169
MELCO Type B	1024	216	200
OAS	874	252	206

II. Material Preparation

A. Cabling

Nb_3Sn strands with KSTAR HP-III specification are used to fabricate the cables for TF coil. MELCO (Mitsubishi Electric Corporation) and OAS (Otokumpu Advanced Superconductor) supply the 8-mm rods. They are drawn to 0.778-mm diameter at Nexans Korea and finally become 0.78-mm strands after chrome plating at KISWIRE. Electrical properties of the strands are shown in Table I [2].

Internal voltage-tap sensors (VTS) are installed in KSTAR magnets for the quench detection. There are four candidate positions of VTS insertion inside the CICC: center of the final cable ($3 \times 3 \times 3 \times 3 \times 6$), valley of the final cable, center of the final sub-cable ($3 \times 3 \times 3 \times 3$), and center of the triplet. The valley of the final cable is the most vulnerable to noises and the triplet is the least [3].

We fabricated three dummy cables to check the possibilities of the sensor insertion candidates and to choose the better twist pitches related with cable losses such as coupling, eddy current, and hysteresis losses.

Regarding the three candidates for sensor insertion mentioned above, the resistance of each sensor, which was used to check the position of termination, was measured at each stage. We found that the center of the final cable was the only place where the sensor could survive the CICC jacketing work. Finally six VTS's are inserted at the center of the final cable.

Roll dies are used to control the size and surface quality of the final cable. The four sets of roll dies, two vertical roll and two horizontal rolls, are used. The vertical and horizontal rolls are installed alternately with die diameters changing gradually $24.0 \rightarrow 23.4 \rightarrow 22.8 \rightarrow 22.4$ mm.

At the final stage of cable fabrication, the cable is wrapped with the thin stainless-steel strip, 30 mm wide and 0.05 mm thick, with 20% overlap at each side.

TABLE II
CHEMICAL COMPOSITION OF INCOLOY 908

Ni	Cr	Nb	Ti	Al	Si	Mn	C	Fe
49.0	4.0	3.0	1.5	1.0	0.15	0.04	0.01	Bal.

TABLE III
MECHANICAL PROPERTIES OF INCOLOY 908 (HEAT TREATED)

Temp. (K)	YS (MPa)	TS (MPa)	Elongation (%)	Thermal contraction (from 700°C)
4	1227	1892	28.5	−1.1
298	1075	1443	16.5	−0.94

B. Jacketing

Incoloy 908 is designed to match the thermal expansion coefficient of Nb_3Sn strand because Jc (critical current density) of Nb_3Sn superconducting strand is reduced by strain. [4]. Incoloy 908 is a Ni-Fe alloy and has high tensile strength and high fracture and impact toughness. It also has fatigue crack growth resistance and good ductility and is metallurgically stable and weldable. The chemical composition and the mechanical property of Incoloy 908 are shown in Tables II and III [5]. The general micro-structure of Incoloy 908 is a single phase austenitic structure. The strengthening is achieved by precipitation of Υ'[(Ni_3 (Al,Ti,Nb))] during the Nb_3Sn superconductor reaction heat treatment [6].

The tube mill process is used for the fabrication of CICC, which consists of forming, welding, sizing and squaring procedures. A strip is wrapped around the superconducting cable and welded. A welded sheath should be quenched immediately by water and the welding bead is ground by bead grinding machine. Then, the tube is formed to the final dimension of CICC, which is shown in Fig. 1. Considering the process, the specification of the strip, which is listed in Table IV, is determined. For TF CICC, the cross sectional area of the strip is 11.4% larger than that of TF conduit and the strip length is increased during the process accordingly.

III. CICC FABRICATION PROCEDURE

A. Cabling

The optimal arrangement was obtained with the aid of a computer programming as shown in Table V. The target was to minimize the difference between the number of the MELCO strands and the number of OAS strands in each and every sub-cable.

TF1-3 were fabricated with about 640 m in length and 22.3 mm diameter. We measured the resistance of all sensors, between the termination points and the CICC end. The resistance per unit length of each sensor had been measured before insertion. We calculated the distances of the termination locations from the CICC end and compared them with the plan values. Table VI shows the results for TF 1 cable. We found the resistances per unit length of the six voltage tap sensors were different. The calculated termination location by the sensor resistances deviated from the intended locations by only 3.7%.

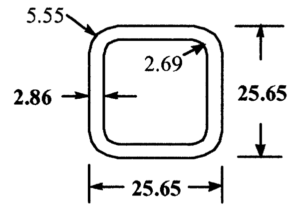


Fig. 1. Dimension of TF CICC.

TABLE IV
STRIP SIZE AND TOLERANCE FOR TF CICC (UNIT: MM)

	TF
Strip size	2.86 T × 94.5W
Tolerances	- Thickness: ± 0.1 - Width: ± 0.03 - Burr: 0.15 Max. - Camber: 6.35 in 2500

TABLE V
OPTIMUM ARRANGEMENT OF SUB-CABLES FOR TF CICC

Stage No.	Total No of Sub Cable	No. of Selection		No. of strand			Subcable No.
		Type -up	Type - low	M	O	C	
1	162			2	0	1	138
				0	2	1	24
2	54	3	0	6	0	3	30
		2	1	4	2	3	24
3	18	2	1	16	2	9	12
		1	2	14	4	9	6
4	6	3	0	48	6	27	0
		2	1	46	8	27	6
5	1	0	6	276	48	162	1

* M: MELCO, O: OAS, C: OFHC

TABLE VI
SENSOR TERMINATION LOCATIONS FOR TF01

Sensor No.	Planned Distance (m)	Resistance (kΩ)	Resistance per unit Length (Ω/m)	Calculated Distance (m)
1	42.1	0.588	12.19	48.2
2	159.3	1.957	12.04	162.6
3	276.5	3.336	11.87	281.1
4	393.7	4.890	11.98	408.2
5	510.8	6.030	11.83	509.9

B. Jacketing

The CICC fabrication procedure is shown in Table VII. The coil of Incoloy 908 strip is supplied by 100∼120 m/coil in length. The length of TF coil is approximately 640 m. This requires that 5 or 6 strip should be weld jointed to make a desired length of TF CICC. The weld of Incoloy 908 becomes hardened by γ' precipitation because the weld of Incoloy 908 experiences nonequilibrium solidification process. During the tube mill process, the strip experiences a strong force to form a desired conduit and the hardened part is not desirable [7]. Post-heat treatment of the weld should be done to reduce the discontinuity of the mechanical properties of the welded zone from the bulk of the strip. To relieve this, water quenching of weldment was performed as a post heat treatment. It could inhibit to form precipitation of Υ' (strengthening phase) after

TABLE VII
THE TF CICC FABRICATION PROCEDURE (UNIT: MM)

Tube mill procedures	TF CICC
Strip	2.86 T × 94.54 W
Welding	Outer dia.: 31.85 Inner dia.: 26.25
Sizing (4% reduction)	Outer dia.: 30.6 Inner dia.: 24.9
Squaring (CICC conduit size)	Outer sqr.: 25.6 × 25.6 × 2.86T Inner sqr.:19.8 ×19.8

TABLE VIII
THE WELDING CONDITION FOR STRIP JOINT

Welding polarity	DCEN
Welding current	70 A
Welding speed	150 mm/min
Shielding gas	12 l/min(Ar) + 0.8 l/min(H_2)
Pilot gas	4 l/min(Ar)
Filler Metal	Incoloy 908

TABLE IX
THE WELDING CONDITIONS FOR TF CICC SHEATHING

Welding polarity	DCEN
Welding current	160A
Welding speed	0.43 m/min
Shielding gas	12 l/min(Ar) + 0.8 l/min(H_2)
Back shielding gas	3 l/min(Ar)
Current slope (for restart welding)	3 sec

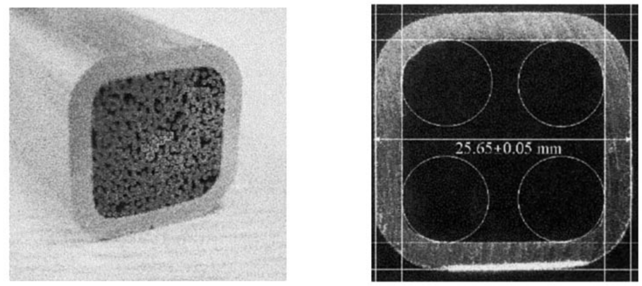
welding. The Vickers hardness test result shows that the hardness of weldment, heat affected zone, and base metal are similar (205∼210 Hv).

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. Strip joint parts are welded by plasma arc welding with Incoloy 908 filler metal because energy density of plasma welding is superior to that of GTAW(Gas Tungsten Arc Welding). The welding conditions are shown in Table VIII.

The Nb_3Sn cable is dispensed from the cable pay off device. The strip is formed to the tube of nominal size through the forming process. The weld seam is maintained on top of the tube. The weld station is the most critical part in the CICC fabrication procedure. The GTAW is used for the welding and the condition is shown in Table IX. The tube was welded into a diameter of 31.85 mm.

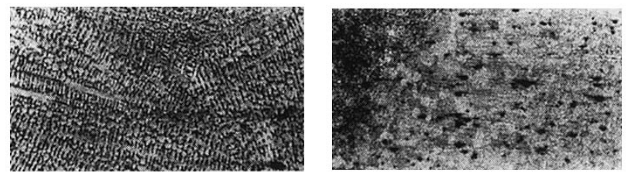
A water spray quench box is used immediately after the welding to reduce the hardening of weldment and minimize the potential for cable damage due to weld heat. The face-bead of the weldment is removed using a bead grinder for the better appearance of CICC. In order not to damage the super conducting cable, It also helps to reduce the final back-bead of the CICC. Before the sizing process, an eddy current test device is used as a non destructive test of weldment.

The sizing stand consists of 8 pairs of driven vertical rolls and 8 pairs of idler side rolls. In case of TF CICC, the sizing stand reduces the tube diameter from 31.85 mm to 30.6 mm. After the reduction of the tube size, a squaring station is used to form the final shape of the CICC.



(a) (b)

Fig. 2. TF 01 CICC (a) and the cross section appearance (b).



(a) (b)

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

IV. DISCUSSION

A LASER measurement device is used continuously to check the final size of CICC to insure the final size CICC. Both width and height of the square were 25.65 ± 0.05 mm. The TF 01 CICC and the cross section appearance shown in Fig. 2. The Thickness of jacket was 2.86 ± 0.05mm, which is within the specification. The superconducting cable can be damaged by the welding back bead in CICC. The height of the welding back bead can be managed below 1 mm and the welding back bead seems not to damage the superconducting cable.

A helium leak test device checks the leak of the CICC. The CICC is pressurized with helium at 30 atm and an automatic leak detector follows the CICC weld. The test result does not detect any leak.

Typical microstructure of Incoloy 908 weld and heat affected zone (HAZ) are shown in Fig. 3. The weld shows a typical cellular-dendritic microstructure. Within the weld zone, a fine grain is visible.

To check the void fraction of the CICC, The dimensions including thickness and corner radius of the CICC were inspected in detail. The results of calculation was above 36%.

V. CONCLUSION

We fabricated TF 1∼3 cables, 640 m long and 22.3 ± 0.1 mm diameter. MELCO superconducting wires were mainly used and OAS wires were also used. The optimal arrangement of OAS wires was investigated to make the cable as homogeneous as possible. We investigated the location for VTS insertion, where VTS could be inserted without any damage, and found the center of the final cable was the safest place.

The TF CICC fabrication was performed by using tube mill process. The shape, weld, microstructure and void fraction of the TF CICC were sufficiently satisfied with the requirements. Consequently, it can be applied to fabricate other CICC's, which are PF6&7 with STS 316LN+, TF bus, and PF bus.

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