Fabrication of the KSTAR Superconducting CICC

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***Abstract*—A superconducting cable-in-conduit conductor (CICC) is adopted for the Korea Superconducting Tokamak Advanced Research (KSTAR) superconducting magnet system which consists of 16 TF coils and 14 PF coils. The KSTAR Magnet system uses two different types of CICCs—Nb3Sn cable with Incoloy 908 conduit and NbTi cable with 316LN stainless-steel conduit. A continuous CICC jacketing system is developed for the KSTAR CICC fabrication and the jacketing system uses the tube-mill process, which consists of forming, welding, sizing and squaring procedures. The design specification of CICCs and the fabrication process is described. The welding of the Incoloy 908 strip joint is also discussed. The fabrication results including the geometrical specification and the void fraction will be discussed.**

***Index Terms*—Background-field coils, cable-in-conduit conductor (CICC), jacketing, Korea Superconducting Tokamak Advanced Research (KSTAR), PF coils.**

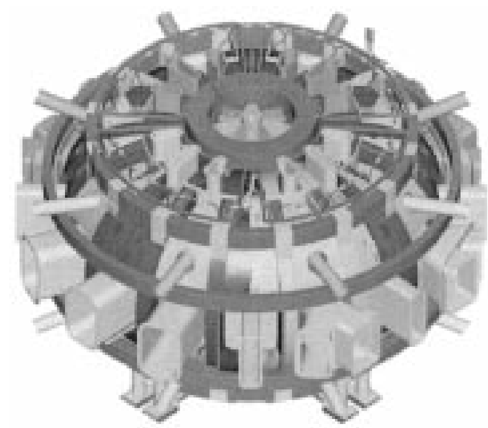

Fig. 1. Arrangement of the KSTAR magnet system.

I. INTRODUCTION

THE Korea Superconducting Tokamak Advanced Research (KSTAR) device is a tokamak with a fully superconducting magnet system which enables an advanced quasi-steady-state operation. The major radius of the tokamak is 1.8 m and the minor radius is 0.5 m with the elongation of 2. The superconducting magnet system consists of 16 TF coils and 14 PF coils. Both of the TF and PF coil system use internally cooled superconductors. The arrangement of the KSTAR coil system is shown in Fig. 1.

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]. TF coils use a Nb3Sn cable-in-conduit conductor (CICC) with a 2.86 mm thick Incoloy alloy 908 (afterward, Incoloy 908) conduit. The Nb3Sn 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/cc at field variation from $+3$ T to -3 T at 4.2 K. 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 bus for the TF coil system uses a NbTi CICC with a modified stainless steel 316LN (STS 316LN+) conduit. The cable pattern of TF bus is also $3 \times 3 \times 3 \times 3 \times 6$. The PF system consists of 8 coils in the central solenoid (CS) coil system and 6 outer PF coils. These can provide 13.6 V-s and can sustain the plasma current of 2 MA for 20 seconds inductively. The CS (PF1-4) and PF5 coils use Nb3Sn in an Incoloy 908 conduit, while the PF6-7 coils use NbTi strands in the STS 316LN+ conduit. The cable pattern of PF coils is $3 \times 4 \times 5 \times 6$. The bus for PF coils uses NbTi strands in the STS 316LN+ conduit.

In order to confirm the coil fabrication procedure, a TF CICC which is 640 m in length has been fabricated and TF00, a full size TF prototype coil, is being fabricated. In order to provide a pulsed background magnetic field for CICC sample tests, a pair of solenoid coils is also being developed. The main coil set of the background field magnet system is designed to provide 8 T at the center with the maximum magnetic field change rate of 3 T/s for 5 s. The main coil uses the same CICC for PF1-5 and will show the ac characteristics of the Nb3Sn PF CICC. Two CICCs of 860 m in length have been fabricated for the main coil set. This paper is focused on the fabrication of the Nb3Sn PF CICC and the fabrication result is discussed.

II. MATERIAL PREPARATION

The critical current density of Nb3Sn superconducting strand is reduced by strain. If the thermal expansion coefficient of the conduit material is same as that of Nb3Sn strand, there is no stain during the cool down of magnets using Nb3Sn CICC and the current density can be maximized. Incoloy 908 is designed to match the thermal expansion coefficient of Nb3Sn strand [2]. The heat treatment condition, chemical composition and the mechanical property of Incoloy 908 are shown in Tables I–III [3]. Incoloy 908 is a Ni based super alloy and has high tensile strength and high fracture and impact toughness, specially in low temperature. It also has fatigue crack growth resistance and good ductility and is metallurgically stable and weldable. The general microstructure of Incoloy 908 is a single phase austenitic structure. The strengthening is achieved by precipitation of Υ'[(Ni_3(Al,Ti,Nb))] during the Nb3Sn superconductor reaction heat treatment [4]. The nominal heat treatment scenario of Nb3Sn strand for the KSTAR magnet system is ramping up

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TABLE I
THE HEAT TREATMENT CONDITIONS OF INCOLOY 908

Annealing (intermediate, final) temperature	980 °C (5-60 minutes, rapid cooling)
Solution annealing (to dissolve ϒ' Precipitation)	1050 °C/hr
Aging temperature range	595-815 °C
Typical grain size	Following cold work: 25-35 μm Following annealing: 85-130 μm
Hardness (following annealing, 700 °C/50hr)	39-40 HRc

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	-1.4

TABLE IV
CHEMICAL COMPOSITION OF 316LN+

C	Mn	Si	Ni	Cr	Mo	Co	N	Fe
0.018	1.52	0.047	11.7	16.7	2.58	0.05	0.16	Bal.

to 460 °C in 6 °C/h and holding for 100 h, then ramping up to 570 °C in same rate and holding for 200 h, and finally ramping up to 660 °C in same rate and holding for 240 h.

The STS 316LN is in the austenitic family of stainless steels which are noted for their corrosion resistance and good fabricability. The chemical composition of the STS 316LN+ for the KSTAR PF6-7 coils are shown in Table IV.

The tube mill process is used for the fabrication of CICC. A strip is wrapped around the superconducting cable and welded. In order not to damage the superconducting cable during the welding, the inner diameter of tube at welding should be larger than the diameter of the cable by 5 mm. Then, the tube is formed to the final dimension of CICCs, which is shown in Fig. 2. Considering the process, the specification of the strip, which is listed in Table V, is determined. For PF CICC, the cross-sectional area of the strip is 12.7% larger than that of PF conduit and the strip length is increased during the process accordingly.

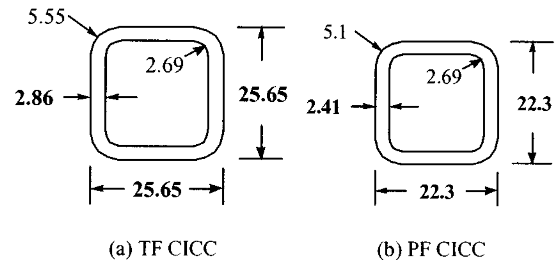

Fig. 2. Dimension of (a)TF and (b) PF CICC.

TABLE V
STRIP SIZE AND TOLERANCES (UNIT mm)

	TF	PF
Strip size	2.86 T × 94.5W	2.41T × 82.1W
Tolerances	- Thickness: ± 0.1 - Width: ± 0.03 - Burr: 0.15 Max. - Camber: 6.35 in 2500	

TABLE VI
THE CICC FABRICATION PROCEDURE (UNIT: mm)

Tube mill procedures	TF CICC	PF CICC
Strip	2.86 T × 94.54 W	2.41 T × 82.1 W
Welding	Outer dia.: 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

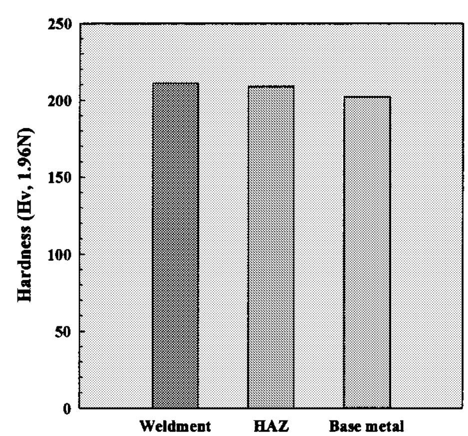

Fig. 3. The Vickers hardness test result.

III. CICC FABRICATION PROCEDURE

The CICC fabrication procedure is summarized in Table VI.

The coil of Incoloy 908 strip is supplied by the form of 100–120 m/coil and the strip should be weld jointed to make a sufficient length of CICC. It is normal that the welded area of Incoloy 908 becomes hardened by precipitation. During the tube mill process, the strip experiences a strong force to form a desired conduit and the hardened part is not desirable [5]. Water quenching of the weldment 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 inhibit from the forming of the B' precipitation after welding. The Vickers hardness test result shows that the hardness of weldment, heat affected zone, and base metal are similar (205∼210 Hv). Fig. 3 shows the result.

To determine the strip joint angle, tensile test has been performed at various joint angle. The room temperature tensile test results are shown in Table VII. The mechanical properties of 45 degree joint is superior to other joints and the strip joint is

TABLE VII
THE TENSILE TEST RESULTS AT VARIOUS JOINT ANGLE

Joint angle	YS(Mpa)	UTS(Mpa)	Elongation
15	355	811	35.3
30	368	863	37.1
45	388	886	38.4

TABLE VIII
THE WELDING CONDITION FOR STRIP JOINT

Welding polarity	DCEN
Welding current	120 A
Welding speed	150 mm/min
Shielding gas	12 l/min(Ar) + 0.8 l/min(H_2)
Filler Metal	Incoloy 908

TABLE IX
THE WELDING CONDITIONS FOR CICC SHEATHING

Welding polarity	DCEN
Welding current	136 A
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

prepared by 45 degrees. Strip joint parts are welded by automatic GTAW (Gas Tungsten Arc Welding) with Incoloy 908 filler metal and the welding conditions are shown in Table VIII.

After the strip joint welding, post-heat treatment, weldment machining, strip cleaning, and strip rewinding to a strip pay-off device are performed in turn. The cable pay-off device is also used to dispense the Nb_3Sn cable. The forming stand forms the strip to the tube of nominal size through a series of progressive roller dies. 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 27.6 mm.

A water spray quench box is used immediately after the welding to minimize the hardening of weldment and reduce the potential for cable damage due to weld heat. The face-bead of weldment is removed using a bead grinder for the better result in sizing and squaring process. 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 driving vertical rolls and 8 pairs of idling side rolls. In case of PF CICC, the sizing stand reduce 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.

IV. DISCUSSION

A Helium leak test device is used to check the defect of the CICC weld. The CICC is pressurized with Helium at 30 atm and an automatic test device follows the CICC weld. The test result does not show any welding problem, yet. The cross section of PF CICC is shown in Fig. 4. Both width and height of the square

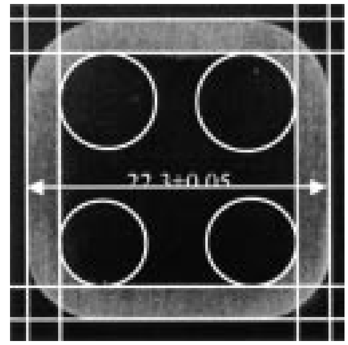

Fig. 4. The cross section of PF CICC (Unit: mm).

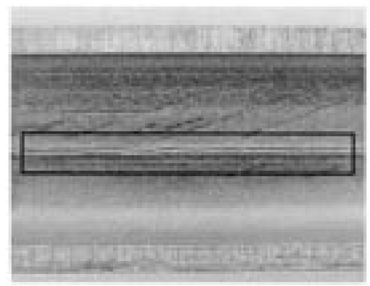

Fig. 5. The welding back bead of PF CICC.

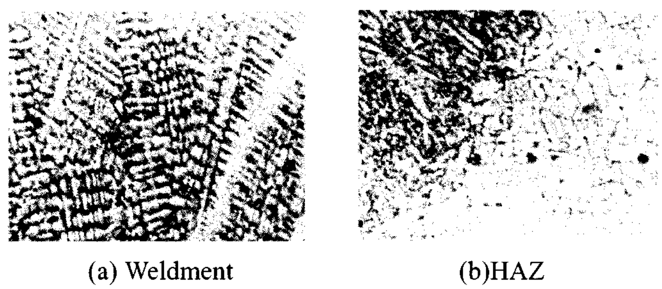

Fig. 6. The microstructure of Incoloy 908 (a) weldment and (b) heat affected zone (HAZ).

were 22.3 $\pm$ 0.05 mm. Considering the deformation during the magnet winding procedure, the difference between the height and width of the CICC is kept intentionally.

The thickness of jacket was 2.41 $\pm$ 0.05mm, which is within the specification. The superconducting cable can be damaged by the welding back bead in CICC. As shown in Fig. 5, the height of the bead can be managed below 1 mm and the welding back bead seems not to damage the superconducting cable.

The microstructure of Incoloy 908 weldment and heat affected zone (HAZ) are shown in Fig. 6. The weld shows a typical cellular-dendritic microstructure with precipitates present within the interdendritic zone. The grain size within the weld zone is actually smaller than that of the HAZ. Porosity and crack is not found both in the weld and the HAZ.

The void fraction of the CICC is calculated. The results of calculation was 36.33%.

V. CONCLUSION

The CICC fabrication procedure was modified. The modification was applied for new PF fabrication procedure, which was proven by experiment, such as shape, weld, and void fraction. The results are sufficiently satisfied for the requirements of PF CICC. Consequently, it will be extended to fabricate other CICCs, which are for TF, PF6&7 with STS 316LN+, TF bus, and PF bus.

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