Jacketing and Repair of the KSTAR CICC

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***Abstract*—The KSTAR (Korea Superconducting Tokamak Advanced Research) superconducting magnet system which consists of 16 TF coils and 14 PF coils adopts a superconducting CICC (Cable-In-Conduit Conductor) type conductor. The KSTAR magnet system uses two different types of CICCs—Nb_3Sn 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. It consists of forming, welding, sizing and squaring procedures. The welding condition of CICCs and the fabrication process is described. The repair of the CICC is also discussed.**

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

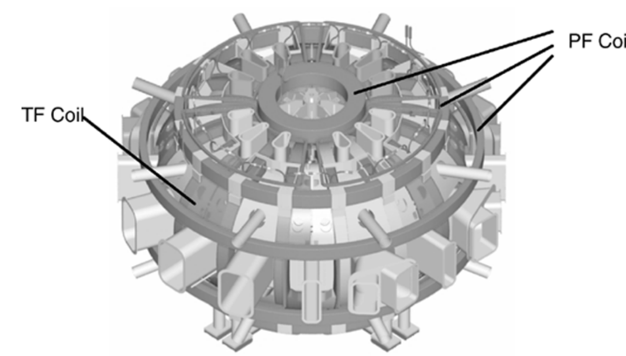

Fig. 1. Arrangement of the KSTAR magnet system.

I. Introduction

THE KSTAR magnet system is a fully superconducting magnet system which enables an advanced quasisteady-state operation. The arrangement of the KSTAR superconducting magnet system is shown in Fig. 1. The superconducting magnet system consists of 16 TF (Toroidal Field) coils and 14 PF coils. Both of the TF and PF coil system 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 and the stored energy is 470 MJ. The nominal current of the TF coils is 35.2 kA with all coils in series. The PF system consists of 8 coils in the CS (Central Solenoid) coil system and 6 outer PF coils. These can provide 13.6 V-sec and can sustain the plasma current of 2 MA for 20 seconds inductively [1]. TF coils and PF1$\sim$5 Coils use a Nb_3Sn CICC (Cable-In-Conduit Conductor) with a 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/mm2 at 12 T, 4.2 K, the hysteresis loss is less than 250 mJ/cc at field variation from $+3$ T to -3 T at 4.2 K and n-value is greater than at 12 T. The PF6$\sim$7 coils use a NbTi CICC with a modified is greater stainless steel 316LN (Stainless Steel 316LN+) conduit

Twelve CICCs of 640 m in length are fabricated for the TF coils. CICCs for the background magnetic field generation coil (900 m $\times$ 2), PF6 (1300 m $\times$ 4), PF7 (1700 m $\times$ 2) and PF 4 lower coils are also fabricated. This paper is focused on the welding of the TF and PF Nb_3Sn CICC, and the fabrication result is discussed. And the repair of the CICC is also discussed.

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II. Material Preparation

A. Cabling

Nb_3Sn strands with KSTAR HP-III specification are used to fabricate the cables for TF and PF 1$\sim$5 coil. Nb_3Sn strands are chrome plated with the thickness of $1 \pm 0.2\ \mu m$. The cable pattern of TF is $3 \times 3 \times 3 \times 3 \times 6$ of 486 strands and the cable pattern of PF is $3 \times 4 \times 5 \times 6$ of 360 strands. The two superconducting strands and one OFHC copper strand are cabled together to become a triplet in the first cabling stage. The cabling pitch of TF and PF conductors are 40-80-160-240-360 mm and 40-80-145-237 mm, respectively. At the final cabling stage, dummy OFHC (0.78 mm $\times$ 7 strands) are inserted at the center of cable to fit the void fraction. 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.

B. Jacketing

Incoloy 908 is used as a jacket material. Incoloy 908 is a Ni-Fe alloy and 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 [2]. Incoloy 908 has high tensile strength, high fracture and impact toughness. It also has fatigue crack growth resistance and good ductility and is metallurgically stable and weldable. The chemical composition is shown in Table I. Table II shows the mechanical property of Incoloy 908 after age hardening heat treatment (660°C, 200 hours) [3].

The general micro-structure of Incoloy 908 is a single phase austenitic structure. The strengthening is achieved by precipitation of $\Upsilon'(Ni_3Al$, Ni_3Ti and $Ni_3Nb)$ during the Nb3Sn superconductor reaction heat treatment [4], [5].

TABLE I
CHEMICAL COMPOSITION OF INCOLOY 908 (wt 5%)

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 II
MECHANICAL PROPERTIES OF INCOLOY 908 (AGE HARDENING 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

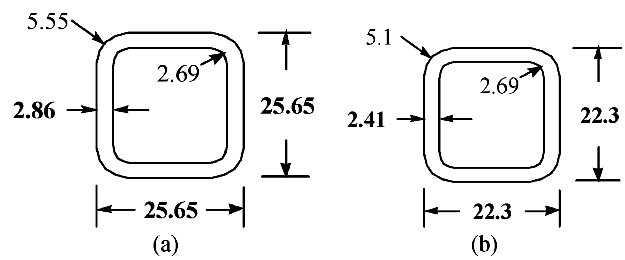

Fig. 2. Final dimension of conduits for TF and PF CICC (unit: mm). (a) TF CICC; (b) PF CICC.

TABLE III
STRIP SIZE AND TOLERANCES FOR CICC (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	

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 conduits of CICCs, which is shown in Fig. 2. Considering the process, the specification of the strip, which is listed in Table III, is determined.

C. CICC Repairing

The CICC repairing test is performed. Several CICC samples for repair test are prepared. Each sample is fabricated with 1 m in length and drilled with 1 mm diameter hole to make an artificial defect. The area to be repaired is marked with 12 mm on either side of drilling hole. The machining of the groove is performed by milling machine. Fig. 3 shows the sample preparation for repair test.

The repair welding is performed by GTAW (Gas Tungsten Arc Welding) in one pass using Incoloy 908 filler to fill the groove. High purity helium atmosphere (greater than 99%) is required inside of the CICC during welding process. After welding, the weld is grinded and several mechanical tests are performed.

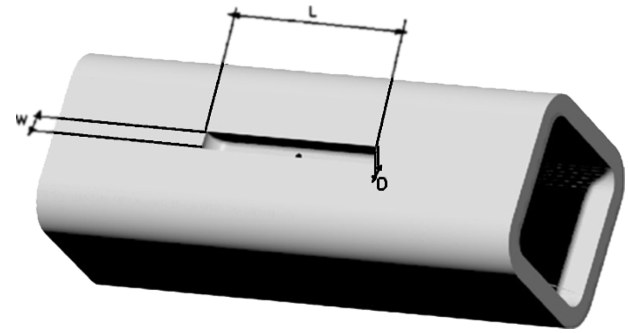

Fig. 3. CICC Sample for repair test (W: width, L: length, D: depth).

III. CICC FABRICATION PROCEDURE

A. Jacketing of CICC

The length of TF coil is approximately 640 m and the length of the strip supplied is 100∼130 m. This requires that 5 or 6 strip should be weld jointed to make a desired length of TF CICC. Strip is joined by automatic GTAW (Gas Tungsten Arc Welding) with Incoloy 908 filler metal. After the strip joint welding, post-heat treatment, weld machining, strip cleaning, and strip rewinding to a strip pay-off device are performed in turn.

The Nb_3Sn cable is supplied 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 because GTAW is widely used for nickel alloys. 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, and consequently, the heat input is greater. Consequently $Ar + H_2$(below 5%) is used for CICC welding since small amounts (below 5%) of hydrogen addition can produces a 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 (more than 99.99%) is critical for preventing welding defects. The 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∼0.8 mm. The welding condition for TF CICCC is shown in Table IV. The tube of TF and PF are welded into a diameter of 31.85 mm and 27.6 mm respectively.

A water spray quench box is used immediately after the welding to reduce the hardening of weld and minimize the potential for cable damage due to weld heat. The face-bead of the weld is removed using a bead grinder for the better appearance of CICC. Not to damage the superconducting cable, it also helps to reduce the final back-bead of the CICC. It can reduce the final back bead more than 1 mm. Before the sizing process, an eddy current test device is used as a non destructive test of weld.

TABLE IV
THE WELDING CONDITIONS FOR TF CICC JACKETING

Welding polarity	DCEN
Welding current	160A
Welding speed	0.43 m/min
Shielding gas	12 l/min(Ar) + 0.5 l/min(H_2)
Back shielding gas	3 l/min(Ar)
Current slope (for restart welding)	3 sec

TABLE V
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 (Jacket 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

TABLE VI
THE SAMPLE PREPARATION FOR REPAIR TEST

Sample No.	Machining Length(mm)	Machining width(mm)	Machining Depth(mm)	Welding Current(A)
1	25.4	2	1.7	70
2	25.4	1.7	1.7	70
3	25.4	3	1.9	75
4	25.4	1.5	1.7	75
5	25.4	2	1.7	75

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. The CICC fabrication procedure is summarized in Table V.

B. Repair Test of CICC

The test sample is machined with a width of 1.7∼3.0 mm and a depth of 1.7∼1.9 mm. The repair welding is performed at welding current of 70∼80 A. The welding is started from 3∼5 mm ahead of the groove and finished 3∼5 mm past the end of groove. Incoloy 908 filler metal is used sufficiently to fill the groove above the level of the base jacket. Table VI shows the each sample preparation for repair test.

The temperature of cable is measured during repair welding since the temperature of $\mathrm{Nb_3Sn}$ strands affects the superconducting performance. The temperature is less than $200^\circ\mathrm{C}$ and this temperature can not affect the superconducting performance.

After repair welding, several tests are performed. Helium leak check (as welded) is performed using helium leak detector. The sensitivity of detected leak rate is 5×10^{-6} mbar l/sec. The repaired CICC is bended for bending test. After the bending test, the inside of the CICC is filled with helium and the leak check is performed in the vacuum chamber $(1 \times 10^{-6}$ Torr$)$ using

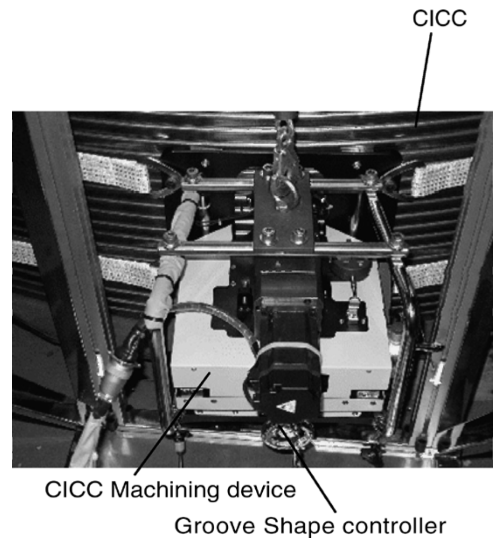

Fig. 4. CICC machining device for repair.

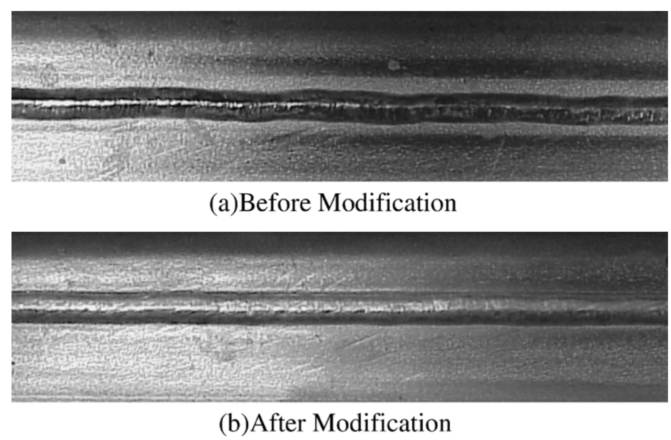

Fig. 5. Welding back bead (a) before modification, (b) after modification.

helium leak detector. And then Helium leak check at low temperature $(-196^\circ\mathrm{C})$, heat treatment (660°C, 240 hours), helium leak check at low temperature $(-196^\circ\mathrm{C})$ are also performed. As a result of repair test, all sample passed the repair test. It is possible to use all sample conditions

After the repair test, the optimum condition is selected for CICC repair. The optimum machining width and depth are 2 mm and 1.7 mm respectively, and an welding current of 70 A is the optimum condition.

On the basis of repair test, repair device is developed. The CICC machining device for repair is shown in Fig. 4. The repair device can move along CICC spool and it can make the groove for repairing around the leak point. It can control groove depth and width using groove shape controller.

IV. DISCUSSION

To ensure optimum welding condition, the CICC tube mill equipment is modified. As a result of modification, the distance between CICC sizing part and welding part is reduced to prevent circular tube twisting and vibration. It can give better uniform welding bead. Welding back bead after modification is shown

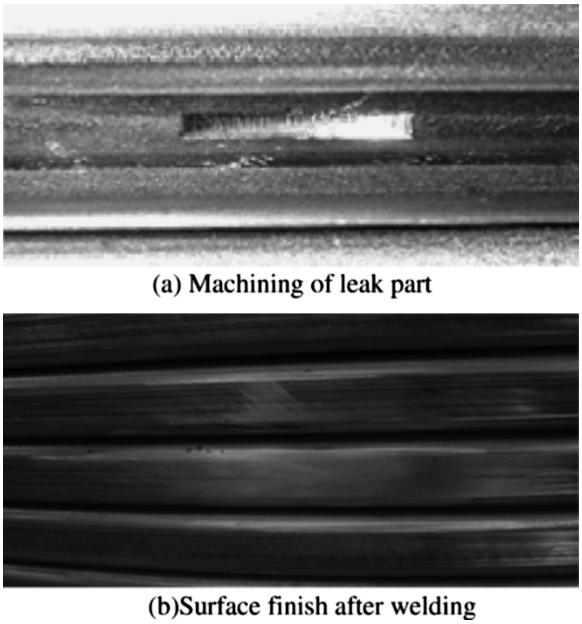

Fig. 6. Machining (a) and surface finishing part (b) of repair process.

in Fig. 5. The new welding bead is better than previous welding bead.

The cross section of TF and PF CICC are inspected. Both width and height of the TF CICC were 25.65 $\pm$ 0.05 mm and those of the PF CICC were 22.3 $\pm$ 0.05 mm. The thickness of TF jacket and PF jacket were 2.86 $\pm$ 0.05 mm, 2.41 mm $\pm$ 0.05 mm which is within the specification. A LASER measurement device is used continuously to check the final size of CICC to ensure the final size CICC.

A helium leak test device is used to check the defect of the CICC weld. The sensitivity of detected leak rate is 5×10^{-6} mbar l/sec. The CICC is pressurized with helium at 35 atm and an automatic test device moves along the CICC weld. The test device discovered several leak points. The porosity size is below the diameter of 100 μm. To repair the CICC welding defect, the repair process is applied to welding defect. Fig. 6 shows machining and surface finishing part. The repair process is performed until leak is not detected.

To check the void fraction of the CICC, The dimensions including thickness and corner radius of the CICC were inspected in detail. The void fraction of CICC is measured both by calculation and Archimedes' principle. The results of calculation and Archimedes principle were below 36%.

V. Conclusion

The CICC fabrication and welding procedure were modified, because the CICC of TF 1$\sim$6 could not meet the requirement for the conduit development perfectly. The modification was applied for new TF and PF fabrication procedure, which was proven by experiment, such as shape, weld, and void fraction. The results were sufficiently satisfied for the requirements of TF and PF CICC.

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

Consequently, the improved welding process and the repair process can be applied to other CICCs, which are for other TF, PF, TF bus, and PF bus.

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