KSTAR PF 코일 시스템을 위한 CICC 제작

임병수, 이상일, 최정열, 김종수, 추용, 박현기, 김명규, 방성근, 정우호, 박갑래, 백설희, 김기만
삼성종합기술원 핵융합프로젝트팀

Development of CICC for KSTAR PF coil system

B. Lim, S. Lee, J. Choi, J. Kim, Y. Chu, H. Park, M. Kim, S. Baang, W. Chung. K. Park, S. Baek, K.Kim
Samsung Advanced Institute of Technology, Daejon, Korea

bslim@venus.sait.samsung.co.kr

Abstract - A superconducting CICC (Cable-In-Conduit-Conductor) is adopted the KSTAR (Korea Superconducting Tokamak Advanced Research) superconducting magnet system which consists of 16 TF coils and 14 PF coils. For the test of KSTAR CICC, an ambient magnetic field of ± 8 T with a maximum change rate of 20 T/s is required and a background-field magnet system is being developed for SSTF (Samsung Superconductor Test Facility). The CICC for PF1~5 is used as the conductor for background-field coils to check the validity of the PF CICC design. Two pieces of cables have been fabricated and the cable has the length of 870 m and the diameter of 20.3 mm. 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.

1. Introduction

The KSTAR (Korea Superconducting Tokamak Advanced Research) 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 SSTF background magnet system is to provide 8 T magnetic flux density and 20 T/s ramp rate to the conductors.

Main Coil (MC) of the system, which consists of two halves of split solenoids, applies an ambient field of 8 T to the testing objects[1]. With regard to the CICC for the MC, we adopted the same as those of PF1-5 coils to check the validity of the PF CICC design. The conduit material is Incoloy 908 and superconducting strands are Nb3Sn. The cabling pattern is 3x4x5x6. At the last stage, voltage-tap sensors (VTS) are inserted. 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.

2. Cabling and Jacketing of the CICC

2.1 Material Preparation

2.1.1 Cabling

Nb3Sn strands with KSTAR HP-III specification are used to fabricate the cables for MC as well as for PF1~5. MELCO (Mitsubishi Electric Corporation) and IGC (Intermagnetics General Corporation) 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 1 [2].

Internal voltage-tap sensors (VTS) are installed in KSTAR magnets for the quench detection. There are four candidate positions of

Table 4. Strip size and tolerances (Unit: mm)

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

2.2 Methods and results

2.2.1 Cabling

The optimal arrangement was obtained with the aid of a computer programming as shown in Table 5I. The target was to minimize the difference between the number of the MELCO strands and the number of IGC strands in each and every sub-cable.

Table 5. Optimum Arrangement of Sub-Cables for MC

Stage No	No of Sub-cable	No of Selection			No of Strand		
		Type -up	Type -mid	Type -low	M	I	C
2	60				8	0	4
					4	4	4
					6	2	4
3	12	3	2	0	32	8	20
		3	1	1	34	6	20
		0	3	2	24	16	20
4	2	2	3	1	190	50	120
		3	2	1	188	52	120

Two real cables, MC-1 and MC-2 for two split solenoids, were fabricated with about 870-m length and 20.3-mm diameter. We measured the resistance of all sensors for the MC, recalculated the termination locations, and compared them with the plan values as listed in the Table 6. We found the resistance per unit length was different and the difference was 6.2% for MC-1 and 6.4% for MC-2.

2.2.2 Jacketing

The CICC fabrication procedure is summarized in Table 7. 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

Table 6. Resistance of Sensors for MC-1 and MC-2

Coil	Sensor No	Plan Dist(m)	Resistance (KΩ)	Resist. per unit L(Ω/m)	Calc. Dist(m)
MC-1	1	26.8	0.32	11.9	26.5
	2	193.9	2.29	11.9	192.8
	3	361.0	4.28	12.3	348.5
	4	528.1	6.28	11.9	526.1
	5	695.2	7.34	10.7	684.5
	6	862.3	9.09	10.6	857.9
MC-2	1	22.5	0.24	11.1	21.4
	2	189.6	2.00	10.8	185.0
	3	356.7	4.23	12.4	340.0
	4	523.8	6.24	12.5	500.4
	5	690.9	8.19	12.4	661.6
	6	858.0	10.18	12.4	820.3

strong force to form a desired conduit and the hardened part is not desirable [6]. 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 γ'[(Ni_3(Al,Ti,Nb))] precipitation after welding. The Vickers hardness test result shows that the hardness of weldment, heat affected zone, and base metal are similar (205-210Hv).

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 8. The mechanical properties of 45 degree joint is superior to other joints and the strip joint is prepared by 45 degree.

Table 7. The CICC Fabrication Procedure (Unit: mm)

Tube Mill Procedures	TF CICC	PF CICC
Strip	2.86T×94.54W	2.41T×82.1W
Welding	Outer dia.: 31.85 Inner dia.: 26.25	Outer dia.: 27.6 Inner dia.: 22.6
Sizing	Outer dia.: 29.3 Inner dia.: 23.7	Outer dia.: 26.5 Inner dia.: 21.5
Squaring (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

Table 8. 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

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 9.

Table 9. The welding conditions for strip joint

Welding Polarity	DCEN
Welding Current	120 A
Welding Speed	150 m/min
Shielding Gas	12 l/min(Ar)+0.8l/min(H_2)
Filler Metal	Incoloy 908

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 Nb3Sn 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 10. The tube was welded into a diameter of 27.6 mm.

Table 10. 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 restarting)	3 sec

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 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.

2.3 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. The test result does not show any welding problem. The cross section of PF CICC is shown in Fig. 2. Both width and height of the square were 22.3 ± 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 ± 0.05mm, which is within the specification.

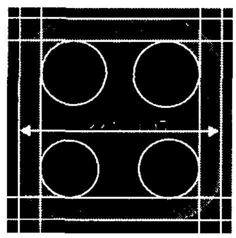

Fig. 2. The cross section of PF CICC (Unit: mm)

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%.

3. Conclusion

We fabricated two sets of cables, 870 m long and 20.3±0.1 mm diameter, one for each half of the MC. Two sets of cabling pitches were tested with various dummy cables fabricated and 40x80x145x237 mm was selected finally. MELCO superconducting wires were mainly used and IGC wires were also used. The optimal arrangement of IGC 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 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.

[REFERENCE]

[1] S. Baang et al., The Background Magnets of the Samsung Superconductor Test Facility (SSTF), IEEE Trans. Appl. Supercond., Vol. 11, No. 1, pp 2082-2085, 2001.

[2] M. Kim et al., The results of performance tests of superconducting wires for KSTAR magnets, Physica C, submitted for publication.

[3] J. H. Schultz, Signal/Noise voltages in KSTAR internal voltage sensor candidates, KSTAR Doc. No: KSTAR-USMIT-JHSchultz-102600-01, October 26 2000.

[4] M. Morra., Alloy 908-Anew high-strength, low coefficient thermal expansion alloy for cryogenic applications, M.S Thesis, MIT, 1989

[5] L. Toma et al., Incoloy alloy 908 Data hand book , MIT, C. J. Kaufman, Rocky Mountain Research Laboratories, Boulder, CO, personal communication, 1992.

[6] C Jang et al., Development ofhigh toughness weld for Incoloy 908, Adv. Cry. Eng. Mat., Vol. 40, pp. 1323-1330, 1994