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# Development of the KSTAR Superconductor

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*Abstract*-- **The magnet system of KSTAR(korean Superconducting Tokamak Advanced Research) is consisted of 16 TF (Toroidal Field) coils and 14 PF (Poroidal Field) coils. Internal cooling CICC(Cable in Conduit Conductor) type conductor is used for both of TF and PF coil systems. The conduit material for $Nb_3Sn$ cable is Incoloy 908 and 316LN stainless-steel was used as conduit material for NbTi cable. $Nb_3Sn$ CICC is used for all TF coils and PF1-5 coils while NbTi CICC is used for PF6 and 7 coils. $Nb_3Sn$ and NbTi strands were made for KSTAR superconducting strand. They are satisfied with KSTAR superconducotr requirements. The $Nb_3Sn$ strands supplied from three companies; MELCO (Mitsubishi Electric Co.), OAS (Outokumpu Advanced Superconductor) and KAT (Kiswire Advanced Technology) were used. A special CICC jacketing system is developed for the KSTAR CICC fabrication which uses the tube-mill process consisted of forming, welding, sizing and squaring procedures. The procedures for cabling and jacketing of CICC for TF and PF coils and their results including the geometrical specification and characteristics of strands are described.**

## 1. INTRODUCTION

The mission of the KSTAR is to demonstrate a advanced and stable superconducting tokamak to achieve a capability of steady state operation. The use of superconducting magnet is essential to achieve this goal. The KSTAR 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 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 $Nb_3Sn$ CICC with a 2.86 mm thick 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 nominal current of the TF coils is 35.2 kA with all coils in series. The total mass of $Nb_3Sn$ for TF coil fabrication is 15.7 ton.

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-sec(volt-second) and can sustain the plasma current of 2 MA for 20 second 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 total mass of $Nb_3Sn$ strands for PF 1-5 coils and NbTi strands for PF 6-7 coils are 7.7 ton and 9.4 ton, respectively.

In this paper, we will describe the fabrication procedure of the KSTAR $Nb_3Sn$ conductor and the fabrication result will be also discussed.

## 2. STRAND AND CABLING

KSTAR $Nb_3Sn$ strands are supplied from the three companies; MELCO (Mitsubishi Electric Co.), OAS (Outokumpu Advanced Superconductor) and KAT (Kiswire Advanced Technology). The inside of the strands for the KSTAR conductor are composed of fine nibium filament(3-5 μm) to reduce AC loss. It can also prevent from sintering of each filaments after heat treatment and can reduce the hysteresis loss below 250 mJ/cm$^3$ for field variation between +3 T and -3 T at 4.2 K. The strands used in KSTAR conductor are shown in Fig. 1, 2, 3 and its properties are shown in table 1. MELCO strand has 37 subelements and the individual subelement has 224 Nb(niobium) filaments, each of which has a diameter of 3.2 μm. The total number of Nb filaments for MELCO strand is 8288 and maximum piece length is 14 km.

OAS strand and KAT strand have 19 subelements and the number of Nb filament in each subelement is 162 and 182 with a diameter of 4.9 μm and 4.5 μm, respectively. The total number of Nb filaments for OAS strand is 3078 and for KAT strand is 3458. Maximum piece lengths are respectively 13 km and 14 km. OAS strand and KAT strand use Sn(tin) spacers[2]. MELCO strand doesn't use spacer.

$Nb_3Sn$ strands are chrome plated with the thickness of 1 ± 0.2 μm. After chrome plating, the superconducting strands(SC) and copper strands(Cu) are cabled together. The cabling patterns of TF conductor are [(2SC+1Cu)×3×3×3×6+7Cu] including 486 strands. And The cabling patterns for PF conductor are [(2SC+1Cu)×4×5×6+7Cu] including 360 strands. The two superconducting strands and one OFHC(Oxygen Free High Conductivity) copper strand are cabled together to become a triplet in the first cabling stage. The twist pitches of TF and PF cable multiplets are 40-80-160-240-360 mm and

40-80-145-237 mm, respectively. At the final cabling stage, dummy OFHC(0.78 mm x 7 strands) are inserted at the center of the cable to fit the void fraction. At the final stage of cabling, the diameters of TF and PF cables are formed to final size of 22.2 mm and 20.3mm. After the final stage of cabling, the cable is wrapped with the thin stainless-steel strip, 30 mm wide and 0.05 mm thick, with 20 % overlap at each side.

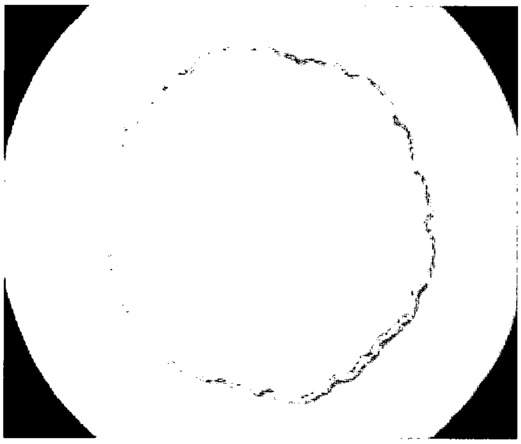

Fig. 1. Cross-section of MELCO strand.

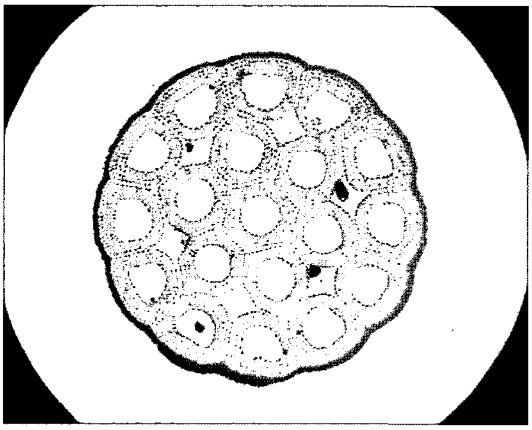

Fig. 2. Cross-section of OAS strand.

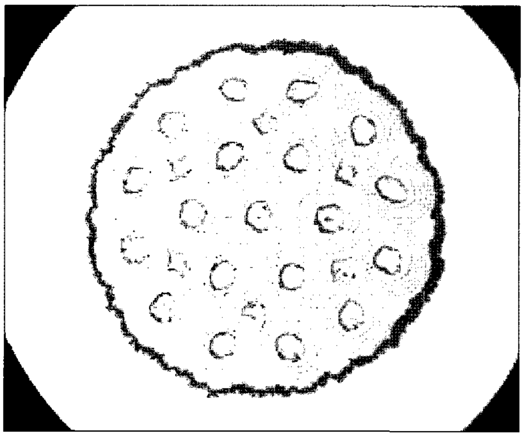

Fig. 3. Cross-section of KAT strand.

TABLE I.
THE KSTAR STRANDS

| Parameters | MELCO | OAS | KAT |
|---|---|---|---|
| Number of subelement | 37 | 19 | 19 |
| Number of filament | 8288 | 3078 | 3477 |
| Average filament dia. (μm) | 3.2 | 4.9 | 4.5 |
| Number of Sn spacers | 0 | 6 | 6 |
| Max. Piece length (km) | 17 | 13 | 15 |
| Twist pitch | 13 | 10 | 12 |
| Average Cu/Non-Cu ratio | 1.56 | 1.59 | 1.55 |

## 3. JACKETING

The tube mill process is used for the fabrication of CICC. Incoloy 908 is used as CICC jacket material for the $Nb_3Sn$ conductor jacketing. Incoloy 908 is selected to match the thermal expansion coefficient of $Nb_3Sn$ strand[3].

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 should be larger than the diameter of the cable by 3 mm. Then, the tube is formed to the final dimension of CICC's. The CICC fabrication procedure is summarized in table 2 and Fig. 4. The superconducting cable is introduced on top of the jacket material. The forming rollers form the jacket material to tube shape to wrap around the superconducting cable. The formed tube then passes into the welding equipment. The tube is welded into the optimum diameter as shown in table 2.

Welded part is cooled by water spray after welding to minimize the hardening and prevent the damage of the cable by heat. The welding bead is removed by bead grinder for the better shape of tube. An eddy current test was performed to detect the defect in welded part

The sizing station reduces the tube to the optimum diameter as shown in table 2. After the reduction of the tube size, a squaring station is used to form the final shape of the CICC. Fig. 5 shows the fabricated KSTAR TF and PF CICC.

After jacketing, the CICC is pressurized with helium to 50 bar and the leak test is performed in the water chamber. Bubble is generated in the water chamber if there is leak in the CICC. 10-20 leaking points are observed in each TF CICC (640m). The diameter of the pore is smaller than 100 μm.

A machining device is developed to grind the repairing part because the part to be repaired should be prepared for welding. It can move along CICC spool and can make the groove for repairing around the leak point. The optimum grove size for repairing is width of 2 mm and depth of 1.7 mm. The repair welding is performed sequentially on the repaired part after the leak test. 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 welding bead is grinded for surface finishing [3]. There is no leak was detected by leak test.

TABLE II
THE KSTAR CICC FABRICATION PROCEDURE (UNIT: MM).

| Procedures | TF CICC | PF CICC |
|---|---|---|
| Strip | Thickness: 2.86<br>Width: 94.54 | Thickness:2.41<br>Width: 82.1 |
| Welding | Outer dia: 31.85<br>Inner dia.: 26.25 | Outer dia.: 27.6<br>Inner dia.: 22.6 |
| Sizing<br>(4% reduction) | Outer dia.: 29.3<br>Inner dia.: 23.7 | Outer dia.: 26.5<br>Inner dia.: 21.5 |
| Squaring<br>(conduit size) | Outer sqr.: 25.6 × 25.6<br>Inner sqr.:19.8 ×19.8 | Outer sqr.: 22.3 × 22.3<br>Inner sqr.:17.3 ×17.3 |

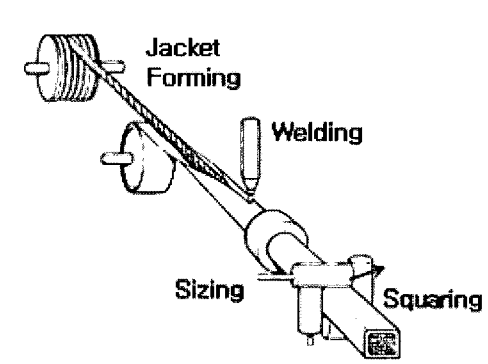


Fig. 4. KSTAR jacketing Process.

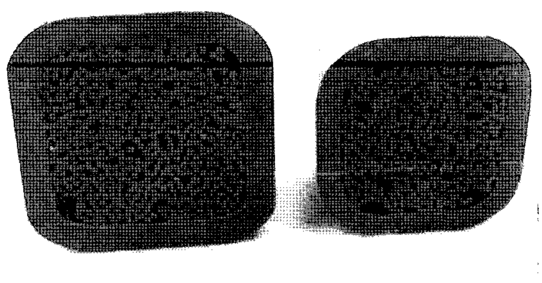

Fig. 5. Cross-section of KSTAR TF and PF CICC.

## 4. REACTION HEAT TREATMENT OF CONDUCTOR

Two large vacuum furnaces were made for KSTAR TF and PF coil heat treatment with a diameter of 5.8 m and 6.4 m, respectively. They can maintain temperature with accuracy of ± 5 ℃. And also they can control vacuum below $5\times10^{-5}$ torr and can maintain oxygen content below 0.1 ppm in order to prevent from SAGBO(Stress Accelerate Grain Boundary Oxidation) for the Incoloy 908 jacket. The SAGBO occurs at the concurrent condition when the temperature ranges from 550 ℃ to 800 ℃, tensile strength is greater than 200 Mpa, oxygen concentration is greater than 0.14 ppm. The heat treatment for KSTAR $Nb_3Sn$ strand was performed as shown in Fig. 6, and entire heat treatment takes about 6 weeks including ramping and cool down time. Prior to the heat treatment, the coil is pressurized with helium at 9 atm and the leak test is performed in the vacuum furnace at $5\times10^{-5}$ torr. During heat treatment, the inside of the CICC is purged with pure argon gas at 6 bars to prevent SAGBO problem of the inside CICC. After the heat treatment, the coil is pressurized with helium at 9 bar and the leak test is performed in the vacuum furnace at $5\times10^{-5}$ torr. Fig. 7 shows inside of vacuum furnace with TF coil.

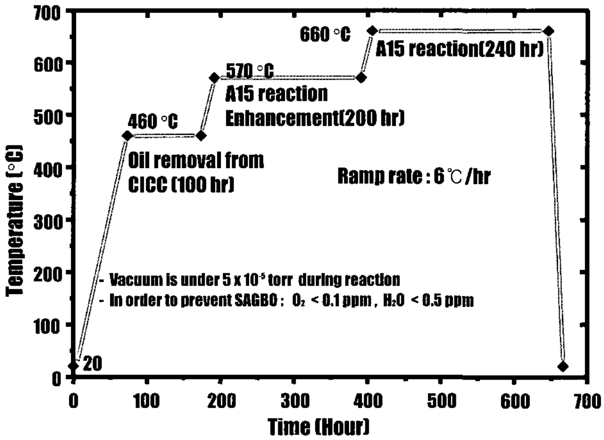


Fig. 6. KSTAR heat treatment scenario.

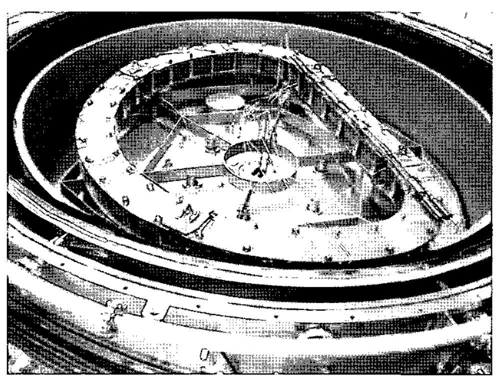

Fig. 7. Inside of vacuum furnace with TF coil.

## 5. RESULTS AND DISCUSSION

After the coil heat treatment is completed, the electrical properties is measured to estimate KSTAR strands which used in KSTAR TF and PF coil. OAS and MELCO strands were used in each TF coil and PF1-4 coils. OAS and KAT strands were used in PF5 coils. The coil heat treatment is accompanied by each company strand sample. 5 samples for each company strand are prepared to measure electrical properties.

The $J_c$(Critical Current Density) of the strand samples are obtained an average of 800 A/mm$^2$ at 12 T and 4.2 K. Jc is calculated from $I_c$(Critical Current) and Cu to non-Cu area. Fig. 8 shows the critical current density with an applying external magnetic field. Hysteresis loss of strand samples is also measured. The average value of the samples is below 224 mJ/cm$^3$ for field variation between +3 T and -3 T at 4.2 K which are in agreement with the specifications.

A laser measurement device is used to measure the final dimension of the CICC continuously. Both width and

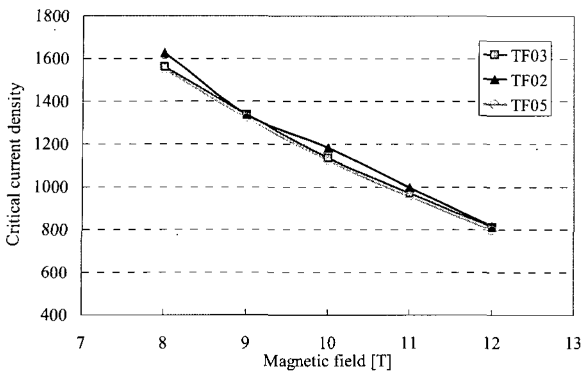


Fig. 8. Critical current density of strand used in several TF coil as a function of magnet field.

height of the TF CICC were 25.65 ± 0.05 mm and those of the PF CICC were 22.3 ± 0.05 mm. After jacketing is completed, 5 CICC samples are prepared for CICC test. Each sample is fabricated with 100 mm in length to examine welding back bead and void fraction. The CICC jacket is removed to inspect the welding back bead and the cable damage. The height of the welding back bead is below 1 mm and the welding back bead does not damage superconducting cable.

The void fraction of the CICC is measured both by calculating from measured dimension of CICC 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 5 TF CICC samples are respectively 34.4 % and 32.5 %.

On the basis of the CICC fabrication process, The CICC for all the TF and PF coils is fabricated successfully.

## 6. CONCLUSION

The KSTAR superconducting $Nb_3Sn$ strands are supplied from the three companies MELCO (Mitsubishi Electric Co.), OAS (Outokumpu Advanced Superconductor) and KAT (Kiswire Advanced Technology). Electrical properties such as the critical current density, hysteresis loss sufficiently satisfied the requirement.

The KSTAR CICC was fabricated by tube mill process. The shape, weld and void fraction of the CICC sufficiently satisfied the requirement.

The high performance KSTAR superconductor will contribute to make KSTAR a premier facility for development of steady-state high-performance modes of tokamak operation.

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