Journal of the Korean Physical Society, Vol. 49, December 2006, pp. S240∼S244

Current Status of the KSTAR TF Superconducting Magnet Development

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(Received 29 August 2005)

The KSTAR (Korea Superconducting Tokamak Advanced Research) TF magnet system is a fully superconducting magnet system which consists of 16 TF coils. 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. TF coils use a Nb_3Sn superconducting strand with Incoloy alloy 908 (afterward, 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. The nominal current of the TF coils is 35.2 kA with all coils in series. For the fabrication of CICC (Cable-In-Conduit Conductor), a continuous CICC jacketing system is developed, and the procedures of coil fabrication are established to develop the TF coil. The prototype TF coil and the TF 01 ∼ 16 coils are fabricated for the KSTAR superconducting magnet system. The TF17 coil which will be used as a back up coil is under fabrication. The overall TF coil fabrication will be completed by the end of December 2005.

PACS numbers: 52.55.Fa
Keywords: KSTAR, Tokmak, Superconductor

I. INTRODUCTION

The KSTAR device will have a superconducting magnet system which consists of 16 TF coils and 14 PF (Poroidal Field) coils. The KSTAR superconducting magnets use internally cooled, cabled superconductors. Since the KSTAR mission is the achievement of long pulse operation [1], the KSTAR superconducting magnet is an obvious choice for the magnet system.

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 [2]. The nominal current of the TF coils is 35.2 kA with all coils in series. The total mass of the TF magnet system is about 150 tons. Each coil is continuously wound without internal joints and has three internal helium feedthroughs. The coolant used in TF coils is SHe (supercritical helium) with an inlet temperature of 4.5 K and an inlet pressure of 5 bars. The SHe is supplied through the two magnet lead joints and the central helium feedthroughs and is discharged through the other two helium feedthroughs. The design value of the total helium mass flow rate in the 16 TF coils is 300 g/s [3]. The major parameters of the TF coils are summarized in Table 1 [4].

TF coils use a Nb_3Sn CICC with a 2.86 mm thick Incoloy 908 conduit. In order to fabricate the TF coil, TF CICCs which are 640 m in length have been fabricated and the TF coil fabrication procedure has also been developed. The procedures of coil fabrication are CICC leak test, grit blasting and winding, preparation for heat treatment, heat treatment, insulation taping, ground wrapping, vacuum pressure impregnation, and acceptance test. This paper focuses on the fabrication procedure and the fabrication status.

II. CONDUCTOR

1. Cabling

TF coils use a Nb_3Sn superconducting strand which 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 with field variation from +3 T to −3 T at 4.2 K [5]. All Nb_3Sn strands are chrome plated with a thickness of 1 ± 0.2 μm. The cable pattern of the TF coil is 3 × 3 × 3 × 3 × 6 of 486. 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 the TF conductor is 40 − 80 − 160 − 240 − 360 mm. At the final cabling stage, dummy OFHC (0.78 mm × 7 strands) are inserted at the center of the cable to fit the void fraction. At the final stage of cable fabrication, the cable is formed to final diameter of 22.2 mm and then

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Table 1. Major parameters of TF coils.

Parameters	Values
Superconductor / conduit	Nb_3Sn / Incoloy 908
Number of coils	16
Toroidal field at major radius	3.5 T
Peak field in conductor	7.2 T
Operating current	35.2 kA
Stored magnetic energy	500 MJ
Centering force	15 MIN
Number of windings	56 turns
Conductor length per coil	640 m
Overall height	4.2 m
Overall width	3.0 m

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

2. Jacketing

Incoloy 908 is used as a jacket material. Incoloy 908 is a nickel-ferrous alloy and is designed to match the thermal expansion coefficient of Nb_3Sn strand because

J_c(critical current density) of Nb_3Sn superconducting strand is reduced by strain [6,7]. The tube mill process is used for the fabrication of CICC. The benefit of the tube mill process is that it can make CICC continuously and easily with a roll formed jacket while controlling cable insertion. 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 the tube at welding should be larger than the diameter of the cable by 4 mm. Then, the tube is formed to the final dimension of CICCs, which is shown in Fig. 1. The speed of the tube mill process is 0.43 m/min. The CICC fabrication procedure is summarized in Table 2 [8]. The overall TF CICCs including TF prototype (640 m) and TF01-17 (640 m × 17) are fabricated.

Prior to repair, the CICC repairing test is performed to find the optimum repairing condition. Several CICC samples for the repair test are prepared. Each sample is fabricated 1 m in length and drilled with a 1 mm diameter hole to make an artificial defect. 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 a welding current of 70 A is the optimum condition.

To repair the real CICC welding defect, the repair process is applied to the welding defect. The repair process is performed until no leak is detected.

After the repair machining, the repair welding is performed by GTAW (Gas Tungsten Arc Welding) in one pass by using Incoloy 908 filler to fill the groove. High

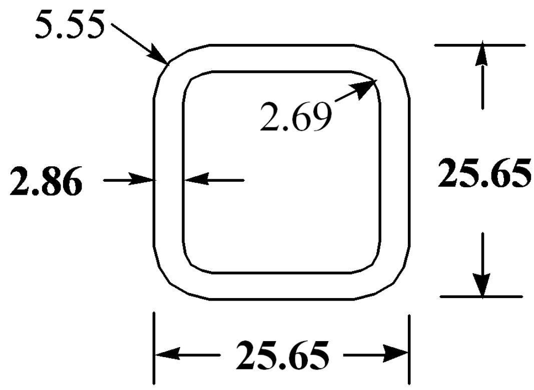
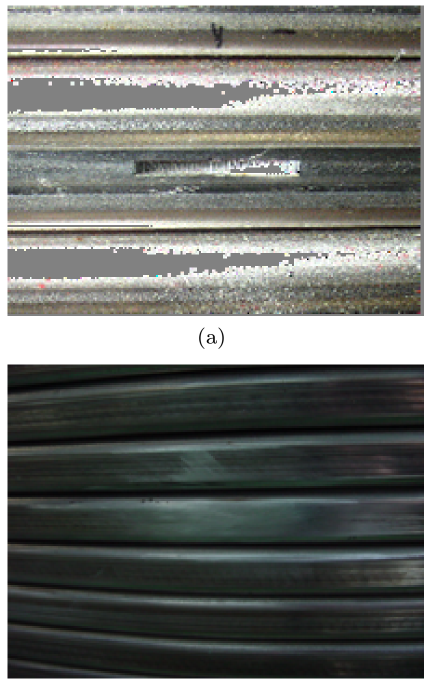


Fig. 1. Dimensions of TF CICC (unit: mm).



(a)

(b)

Fig. 2. Machining (a) and surface finishing part (b) of repair process.

purity helium atmosphere (more than 99 %) is required inside of the CICC during the welding process to prevent oxidation of welding back bead. After welding, the weld is ground as a surface finishing treatment [9]. Fig. 2. shows the machining and surface finishing part.

III. TF COIL FABRICATION

1. CICC Leak Test

A CICC leak check is performed to check the defect of the CICC weld. During the sizing process, an eddy current test device is used for a non destructive test of

Table 2. 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 × 2.86 T, Inner sqr.: 19.8 ×19.8

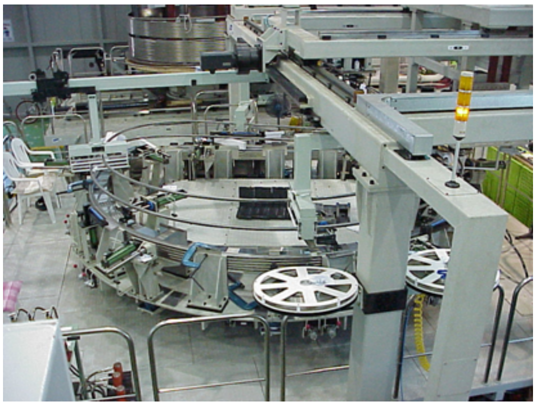


Fig. 3. Winding station for TF coils.

CICC welds. The eddy test result does not show any welding problem.

After jacketing, the CICC is pressurized with helium at 50 atm and the leak check is performed in a water chamber. 10 ∼ 20 leak points are discovered after a leak check of each 640 m TF coil. The average porosity size is below the diameter of 100 m.

2. Winding

Several bending rollers straighten the CICC before the TF winding process, and the straightening accuracy is maintained below 0.5 mm/m. Zirconia bead blaster is used to reduce the residual stress of the CICC surface after CICC straightening. TF winding is carried out by a 3-roll bending process after the CICC straightening and grit blasting. When the driven rollers push the CICC, it proceeds in the forming direction and with the bending roller the CICC is formed into a circle with a constant radius of curvature. The continuous winding scheme without internal joints is adopted to reduce the joint losses. Fig. 3. shows TF winding stations operating for the winding of TF coils. The speed of the winding process is 0.3 m/min. To compensate for the turn insulation gap before heat treatment, a stainless tape is inserted between conductors after winding. The dimensional error in the TF winding pack is maintained below 1 mm.

3. Preparation for heat treatment

The TF winding pack is moved to a heat-treatment jig to fix the winding pack after the winding process. The heat- treatment jig is made to minimize the deformation of the winding pack during the heat treatment. It can prevent such deformation by confining the stainless steel plate and bolt. Fig. 4. shows a heat treatment jig. The material of the jig is 316L stainless steel. 316L stainless steel spacers are filled in the empty space of the layer transition part to minimize deformation of the winding pack during heat treatment. After the heat treatment-jig -assembly, preparation for heat treatment such as feed-through drilling hole formation and joint termination is carried out. When drilling and joint termination are completed, feed-through attachment and joint welding are carried out by GTAW welding. 316L stainless steel is used as a feed-through and joint box material. The helium leak check is performed at each welding part after feed-through and joint box welding [4].

4. Heat treatment

Two large vacuum furnaces are developed for TF and PF coil heat treatment with a diameter of 5.8 m and 6.4 m. They can maintain a temperature of ±5 °C. Coil temperature is measured at 12 points during heat treatment. They can also control vacuum below 5×10^{-5} torr and can maintain oxygen content below 0.1 ppm in order to prevent SAGBO (Stress Accelerate Grain Boundary Oxidation) for the Incoloy 908 jacket. SAGBO occurs when the temperature ranges from 550 °C to 800 °C, tensile strength is greater than 200 Mpa, and oxygen concentration is greater than 0.14 ppm simultaneously. The nominal heat-treatment scenario of Nb_3Sn strand for the KSTAR magnet system is ramps up to 460° at 6 °/hour and holds for 100 hours, then ramping up to 570° at the same rate and holding for 200 hours, and finally ramping up to 660° at the same rate and holding for 240 hours. The whole duration of heat treatment is about 6 weeks, including ramping-up and cool-down time. During the heat treatment, the inside of the CICC is purged with pure argon gas at 6 bars to prevent the SAGBO problem at the inside CICC. Before and after the heat treatment, the coil is pressurized with helium at 9 atm

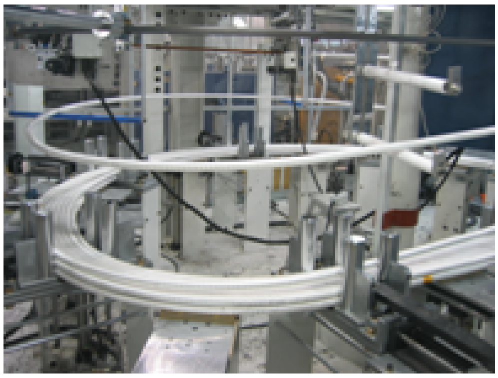
Fig. 4. Heat treatment jig for TF coils.

and the leak check is performed in the vacuum furnace [4].

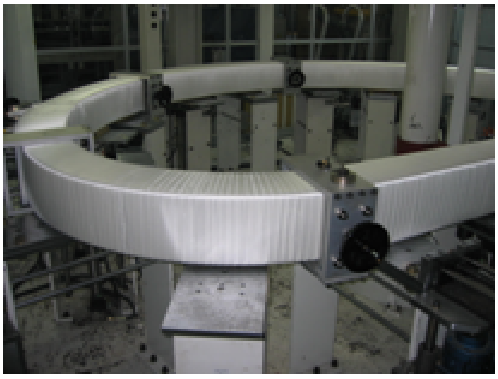
5. Insulation taping

To insulate the TF coil, several taping devices have been developed such as taping head, CICC separating device, CICC re-arrangement fixture and ground wrapping device. By using these devices, each turn of the TF coil is individually separated and the CICC is insulated with 50 % overlapped layers of Kapton and S2-glass tapes. The thickness of Kapton and S2-glass tapes is 0.05 mm and 0.178 mm respectively. During insulation taping, each separated turn of the coil is maintained below 70 cm to prevent Nb_3Sn strand deformation after heat treatment.

CICC is rearranged after insulation taping. S2-glass roving is applied at the corner of CICC to minimize the resin rich area after insulation taping. G10 pieces, which are shaped to fill the empty space of the layer transition area, are also inserted and the coil bundle is ground wrapped by using S2-glass tape. The thickness of S2-glass tape for the ground wrapping is 0.254 mm. The dimensional error in the TF ground wrapping bundle is maintained below 2 mm [4]. Fig. 5. shows insulation taping and ground wrapping devices for the insulation of TF coils.



(a)



(b)

Fig. 5. (a) Insulation taping and (b) ground wrapping for TF coils.

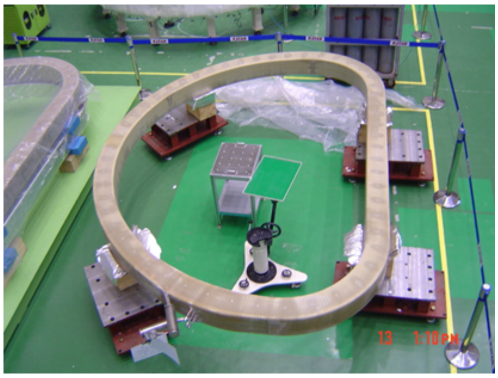


Fig. 6. TF coil after VPI.

6. Vacuum pressure impregnation and acceptance test

After the ground wrapping has been completed, the coil bundle is placed in a molding die and a molding jig is assembled to prepare for vacuum-pressure impregnation. VANICO GY282, HY918, and DY073-1 are used as the epoxy resin, hardener, and accelerator, respectively. An epoxy feeding line is connected from resin mixer to molding jig. The pre-mixed resin is warmed to 40 °C and injected to the molding die. Curing occurs at 80 °C for 12 hours and at 120 °C for 24 hours. Fig. 6. shows a TF coil after VPI. 3-dimensional measurements after VPI, high voltage test and flow rate test are performed as an acceptance test. The flow test was performed at room temperature and pressurization to 4 bars. The distribution of flow rates among cooling channels is maintained within 10 % variation. For the high voltage test, DC hipot voltage was 15 kV and AC hipot voltage was 10 kV. The test result does not show any serious problem. The dimensional error in the full size of the TF coil after VPI is maintained below 2 mm [4].

IV. CONCLUSION

TF CICC and coil fabrication procedures were developed. The results were sufficiently good to satisfy the requirements for a TF Coil. TF CICC including TF prototype (640 m) and TF01-17 (640 m $\times$ 17) are fabricated. The prototype TF coil and the TF1 $\sim$ 14 coils are successfully fabricated. The TF15 $\sim$ 17 coils are under fabrication for the KSTAR superconducting magnet system. The overall TF coil fabrication will be completed by the end of November 2005.

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