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Development of FAIR conductor and HTS coil for fusion experimental device

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Keywords: high temperature superconducting, fusion magnet, FAIR conductor, HTS, high temperature superconductor

Abstract

This study is aimed at the development of high-temperature superconducting (HTS) magnets for application in a fusion experimental device next to the Large Helical Device (LHD). By applying the features of an HTS, high current density and high stability can be balanced. As a candidate conductor, REBCO tapes and pure aluminum sheets are laminated and placed in the groove of an aluminum alloy jacket with a circular cross-section, after joining a lid to the jacket using friction stir welding, and twisting the conductor to homogenize its electrical and mechanical properties. The FAIR conductor derives its name from the processes and materials used in its development: Friction stir welding, an Aluminum alloy jacket, Indirect cooling, and REBCO tapes. Initially, the degradation of the critical current of the FAIR conductor is observed, which was eventually resolved. The development status of the FAIR conductor has been reported.

1. Introduction

The high-temperature superconductors (HTS) are expected to be applied to various fields because of their high critical temperature and critical magnetic field. However, compared to low-temperature superconductors (LTS), when constructing a conductor with a large current capacity using multi-twisting round wires, the second generation HTS REBCO that is essentially a thin tape-shaped wire owing to the crystal structure of the superconducting material restricts the manufacturing method. Consequently, it is difficult to increase the current capacity using multi-twisting tapes, thereby preventing its application to large-scale magnets typified by nuclear fusion.

The superconducting magnet of a fusion device, in which the magnetic field and stress direction of the coil change depending on the location, requires a conductor structure in which the REBCO tapes are covered with a metal jacket material to support the large electromagnetic force. The stored magnetic energy of the coil can be rapidly extracted after the coil quench. To prevent burnout of the coil, it is essential to develop a conductor with a large current capacity capable of reducing the coil inductance.

The HTS conductor with a large current capacity for fusion devices [1] and high-energy physics magnets are being researched and developed in Europe, the United States, Japan, and China. At KIT in Germany, a Robel conductor using REBCO wire is proposed, and is developing it for use in fusion devices and next-generation high-energy accelerators [2]. The tape-shaped REBCO wire is cut out by punching to form a meander shape, and the wires are twisted to form a conductor. At MIT in the United States, a Twisted-Stacked Tape Cable (TSTC) structure in which REBCO tape wires are laminated and then the entire bundle is twisted is proposed [3]. It has been proposed to construct a large current capacity CIC conductor by assembling a number of TSTC wires. Similar conductors based on this TSTC structure have been proposed, including RSCCT conductors from SPC

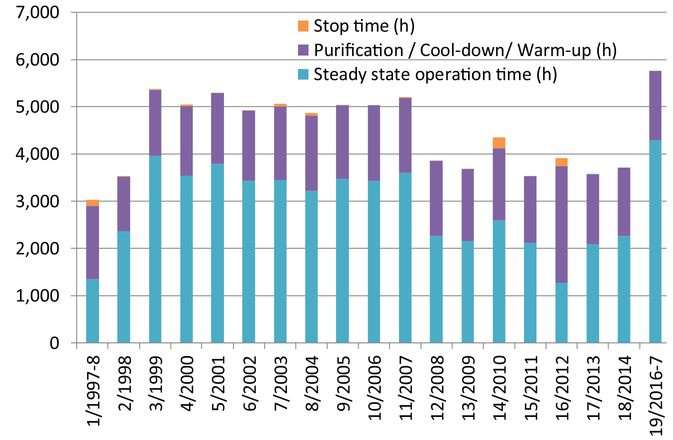

Figure 1. Operational history of LHD.

in Switzerland [4], Slotted CIC conductors from ENEA in Italy [5], CroCo conductors from KIT in Germany [6], and QI conductors from North China Power University (NCEPU) in China [7]. CORC (Conductor on Round Core) conductor is commercialized by Advances Conductor Technologies LLC of the United States [8]. The conductor is constructed by wrapping a REBCO wire around a copper former. Since the wire is spirally wound, it has excellent flexibility as a conductor. High-current CIC conductors for fusion devices and indirect cooling conductors for detectors for high-energy physics have been prototyped by assembling CORC conductors as strands [9]. In collaboration with Tohoku University, NIFS in Japan has proposed the STARS (Stacked Tapes Assembled in Rigid Structure) conductor in which REBCO tape wires are simply laminated and covered with a mechanically strong jacket material [10]. Assuming application to the helical fusion reactor FFHR, a prototype of a 100 kA-class short conductor was successfully tested and a 20 kA-class long conductor is being developed..

However these conductors deteriorate when twisted or bent with short pitch lengths; in particular, irreparable deterioration may occur when using REBCO tapes. Futhermore, the development stage of an HTS conductor capable of producing an actual magnet has not been achieved.

In this study, an HTS conductor (FAIR conductor) with a large current capacity that is easy to wind and handle, and a coil structure (FAIR coil) that incorporates a cooling panel are proposed as a manufacturing technology for large-scale HTS magnets applicable in devices such as fusion devices [11].

2. Operational history of large helical device and its next stage

The Large Helical Device (LHD) at the National Institute for Fusion Science (NIFS) is a heliotron-type fusion plasma experimental device with the world's first completely superconducting magnetic confinement system [12]. The LHD has been operating reliably for more than 20 years since 1998 and has provided stable fusion plasma confinement experimental environment. The operational history of the LHD superconducting system is summarized in figure 1. The total operating time of the system until the end of the 20th cycle in the 2018 fiscal year was 88,822 hs; whereas, the stop time was only 743 hs.

The deuterium plasma experiments started in March 2017, and the LHD experiment entered a new stage of the collected studies. We started the research of HTS helical coils with the aim of applying them to the next experimental device of the LHD.

3. Concept of FAIR conductor and coil

3.1. Large current-carrying capacity of FAIR conductor

The FAIR conductor derives its name from the processes and materials used in its development: Friction stir welding, an Aluminum alloy jacket, Indirect cooling, and REBCO tapes. Figure 2 shows the configuration of the FAIR conductor. The development of a conductor with 12.5 kA at 10 T, 20 K is the target value for the first stage R&D and a conductor with 20.0 kA at 10 T, 20 K is the target value for the HTS helical coils. A high current HTS conductor (FAIR conductor) is required in which the stacked REBCO tapes and high purity aluminum sheets as shock-absorbing materials are placed in the groove of an aluminum alloy jacket of circular cross section. After welding a lid to the jacket using the friction stir welding (FSW), the conductor is twisted to equalize the current distribution between the stacked REBCO tapes and to achieve uniform mechanical and electrical properties.

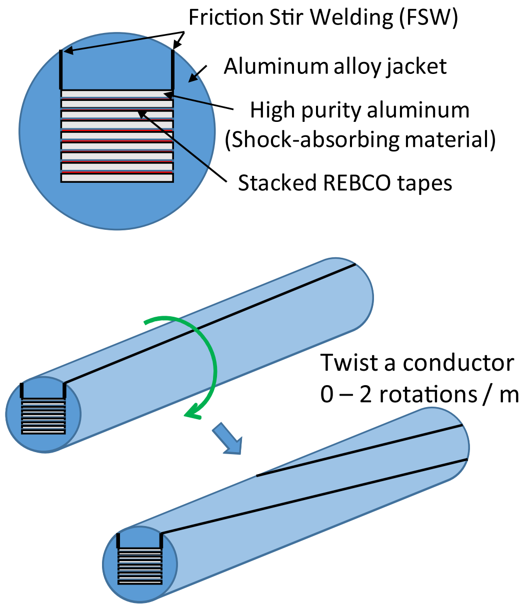

Figure 2. Configuration of FAIR conductor.

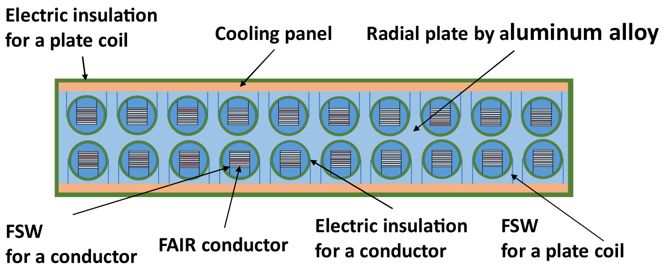

Figure 3. Structure of FAIR element coil.

However, if the lid is jointed to the aluminum alloy jacket through soldering, the joint portion gets damaged while twisting the conductor. Therefore, a mechanically strong lid is indispensable. When an aluminum alloy is coated on a low-temperature superconducting NbTi/Cu strand, the integral molding is performed using an extrusion method that is very common. However, aluminum extrusion in which heat is applied at 673 K (400 °C) or higher, cannot be used to coat HTS wires because their superconducting properties begin to deteriorate when heated up to 473 K (200 °C). FSW is a metal joining technique devised in 1991 by the welding institute (TWI) in the UK. It has the advantage that materials can be joined without raising their temperatures. Therefore, the mechanically strong FSW of the lid of aluminum alloy jacket is essential, otherwise the joint part can be get damaged while twisting the FAIR conductor.

There have been past production examples of heat-treated Nb_3Sn conductors with a rectangular cross-section aluminum alloy jacket covered by FSW [13], but the FAIR conductor is the first REBCO wire to be used.

3.2. Configuration of FAIR coil

Figure 3 shows the structure of the FAIR element coil. Because the FAIR conductor has no cooling channel, a cooling panel is inserted in the coil windings to cool it indirectly.

Figure 4 shows the development of the high-performance two dimensional (2D) HTS coil. The indirect cooling element FAIR coils are stacked. The stacked element FAIR coils are covered with coil case for mechanical reinforcement. Here, the high performance refers to high current density. The current density of the conductor is 110 A mm^{-2} (176 A/mm^2). The current density of coil windings is 50 A mm^{-2} (80 A mm^{-2}) , that is the target value for the first stage R&D and (HTS helical coils).

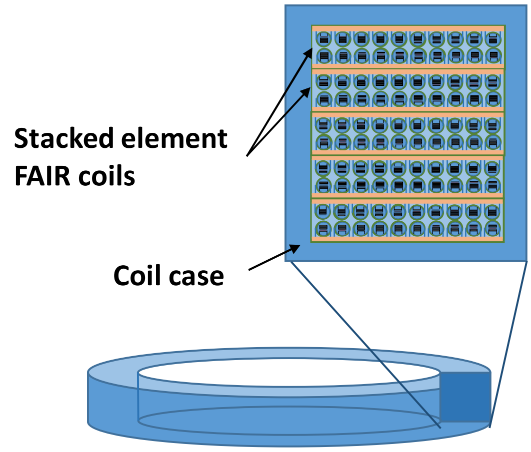

Figure 4. Configuration of 2D FAIR coil.

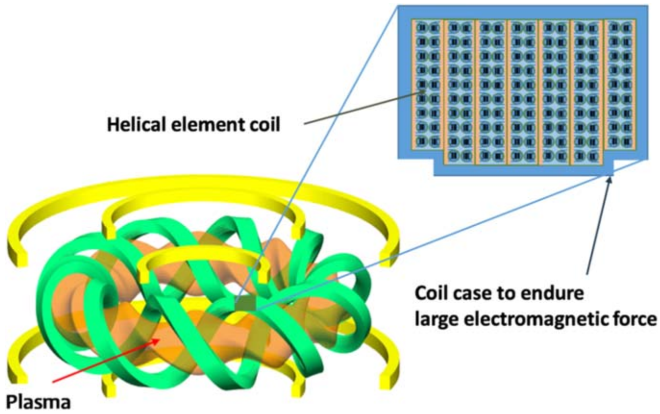

Figure 5. Configuration of 3D FAIR coil.

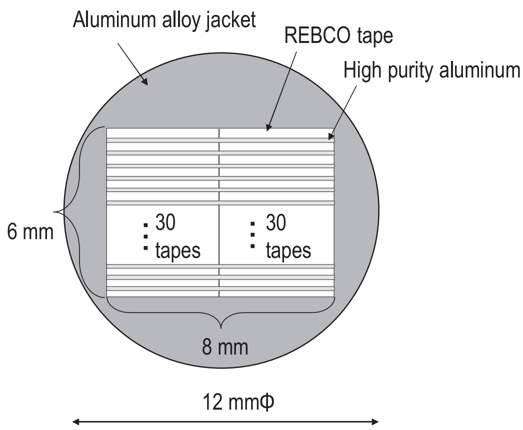

Figure 6. Cross section of FAIR conductor.

3.3. Structure of HTS helical coil

The three dimensional helical coil is also stacked helical element coils and covered with coil case to endure a large electromagnetic force as shown in figure 5. Figure 6 shows the cross section of the FAIR conductor with the rated current of 12.5 kA at the magnetic field of 10 T, and the operating temperature of 20 K. The dimensions of the REBCO tape used are 4 mm wide and 0.1 mm thick. The number of REBCO tapes necessary for the FAIR

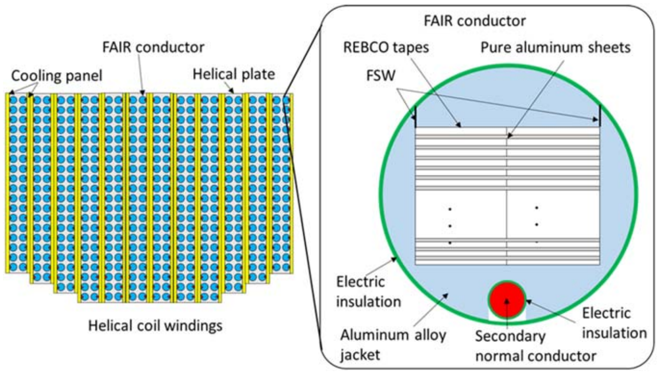

Figure 7. Cross section of HTS helical coil windings.

conductor is 60. The total length of the REBCO tape used is 1,158 km with the major radius of the helical coils as 2 m, which is one of the candidate designs for the next stage of the LHD.

Due to the effect of the helical plate (helical-shaped radial plate), the electromagnetic force applied to the FAIR conductor is considered to be ideally the same as the electromagnetic force applied to one conductor, so that it remains at 17 MPa even under the conditions of a magnetic field of 10 T and a conductor current of 20 kA. However, it is assumed that conductors will be subjected to more stress due to differences in thermal shrinkage for each component material and errors in coil production. The detailed design of the helical FAIR coil has not been completed yet, but the LHD helical coil assumed that the conductor would be subjected to a maximum compressive stress of 120 MPa. It is assumed that FAIR conductors can withstand a stress of 120 MPa.

The HTS coil has the advantage of high stability because of its high operating temperature. However, quench protection is more difficult, compare to the LTS coil. In this study, we propose a new coil-protection method suitable for the FAIR conductor and a coil structure to safely achieve a high current density. Figure 7 illustrates the cross section of the HTS helical coil windings using the FAIR conductor. A normal secondary winding that is electrically insulated by providing a groove of the FAIR conductor is installed, as presented in figure 7. During the excitation of the coil, the HTS coil is connected to a power supply and the secondary winding circuit is kept open; hence, there is no current flow. As the secondary winding takes the same current path as that of the HTS coil, it is possible to detect a quench with high sensitivity by detecting the voltage difference between them. When a quench occurs, the HTS coil is disconnected from the power supply and is connected to an external protective resistor, attenuating the coil current. The secondary winding is short-circuited using a switch, and a current is induced through electromagnetic induction between the normal conducting secondary winding and the primary winding of the HTS coil. The secondary winding heats the FAIR conductor and acts as a quench heater that accelerates the normal transition of the conductor. This accelerates the normal conduction of the HTS coil and enables safe coil protection. The current decay time constant, the voltage generated in the HTS coil, and the energy-recovery rate of the external protection resistor are optimized for use by selecting protection resistance, secondary winding resistance, thermal contact conditions, etc. A quench protection method using secondary winding as a quench heater was proposed along with the results of two-dimensional analysis and three-dimensional simulation using the finite element method at EUCAS2019 invited poster presentation. The results obtained by Y Onodera in, 'Novel HTS coil protection method using secondary windings as a quench heater' are to be published in the Journal of Physics: Conference Series (JPCS).

4. Development and testing of FAIR conductor

4.1. First trial production of FAIR conductor

Figure 8 shows the optimization of the parameters of FSW. We modify FSW conditions, such as FSW position, FSW forward speed, tool size, shape, rotational speed to optimize for the FAIR conductor. During R&D, we observe that it is necessary to use a rotation prevention jig and a rotation prevention groove. Next, we modify the shape of the cross section of the FAIR conductor using a rotational prevention groove.

The temperature rises of the joint during FSW are controlled to be 473 K (200 $^\circ$ C) or less. The quality of FSW joint is ensured by optimizing the tool shape, tool rotational speed, FSW position, etc.

Figure 9 shows the configuration of the first trial production of the FAIR conductor. The sheet thickness of high-purity aluminum is 0.5 mm. The REBCO tape with a width of 4 mm and thickness of 0.1 mm is placed in the upper, middle, and lower sides, and the rest of the structure is laminated using stainless dummy tapes of the

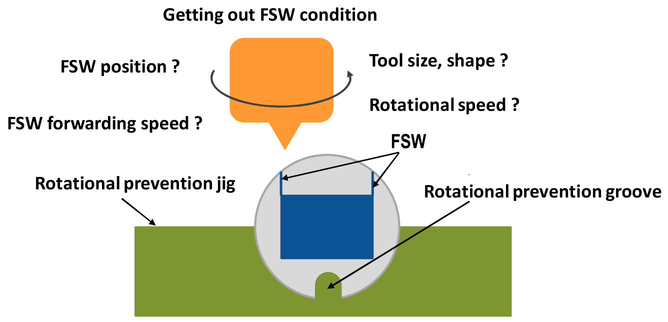

Figure 8. Optimization of FSW.

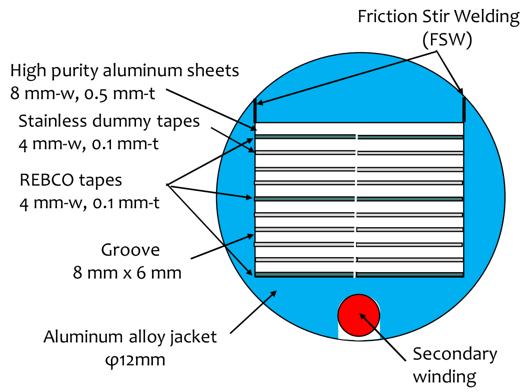

Figure 9. Configuration of first trial production of FAIR conductor.

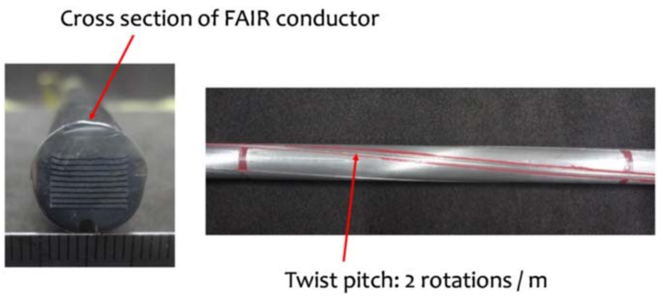

Figure 10. Photograph of first trial production of FAIR conductor.

same thickness. After joining the lid of the aluminum alloy jacket using FWS, the conductor is twisted at the rate of 0 to 2 rotations/m.

Figure 10 shows the photograph of the first trial production of the FAIR conductor with twists of 2 rotations/m. Figure 11 shows the testing setup of the short sample of the FAIR conductor. The 1 m-long short sample (with 6 REBCO tapes) is joined at the bottom with the current return path that includes 20 REBCO tapes. Both top ends of the conductor are connected to the current leads, and the current-carrying test is conducted in liquid nitrogen. To measure the difference between samples, two conductors (No. 1 and No. 2) are tested under the same manufacturing conditions.

The result of measuring the normalized critical current under the electric field condition of 10^{-4} Vm^{-1} is presented in figure 12. The summarized data of normalized critical-current-measurement result normalized with the critical current value 6 times the REBCO tape value (SCS4050-AP manufactured by the SuperPower Inc.) is presented. The circles indicate no rotating conductors. Conductor No.1 and conductor No. 2 exhibit almost the same characteristics in the first current-carrying test. Therefore, only conductor No. 2 was used for the subsequent current-carrying tests and thermal cycle tests in which the sample temperature was increased from liquid nitrogen temperature to room temperature and then re-cooled back to liquid nitrogen temperature.

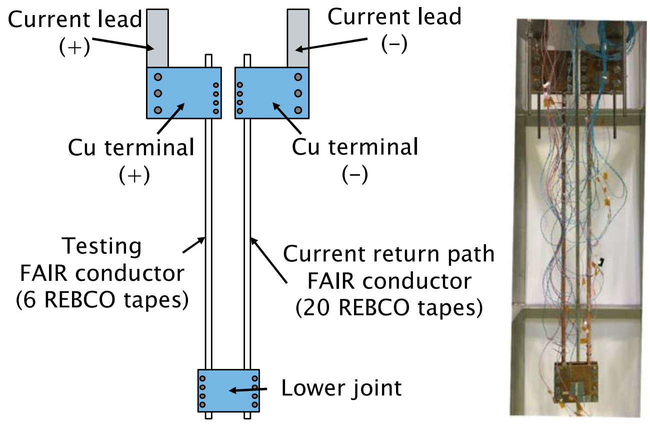

Figure 11. Testing setup of short sample FAIR conductor.

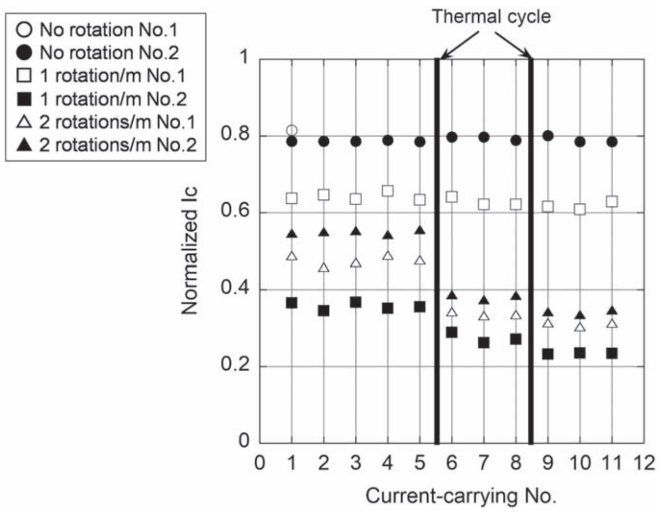

Figure 12. Normalized critical current of first trial production of FAIR conductor.

It was observed that the normalized critical current degraded by 20% even with the conductor that was not twisted.

The data of conductors with twists of 1 rotation/m are denoted by square marks. The degradation of the critical current of the conductors was observed from the beginning, and the degradation progressed with the thermal cycle. Degradation in conductor No. 2 was particularly noticeable.

The data of the critical current of the conductors with twists of 2 rotations/m are shown by triangle marks. The critical current was observed to degrade from the beginning and the degradation progressed with the thermal cycle.

The characteristic difference between the samples developed under the same production conditions was significant, and the quantitative evaluation of the degradation due to the twisting of the conductors could not be obtained from these data.

To investigate the cause of critical current degradation, the severely degraded No.2 conductor with twists of 1 rotation/m was disassembled and the state of the REBCO tapes was observed. Figure 13 shows the check state of the REBCO tapes in this conductor. The REBCO tapes were more severely damaged at the lid section closer to the FSW position, and were not damaged at the bottom of the groove where they were far away from the FSW. The degradation of the REBCO tapes is measured using voltage terminals with interval of 90 mm as shown in figure 14. The tapes at the lid section were severely damaged and could not be measured, the tapes at the middle section were degraded at multiple locations, and the tapes at the bottom section were degraded at two locations in each REBCO tape.

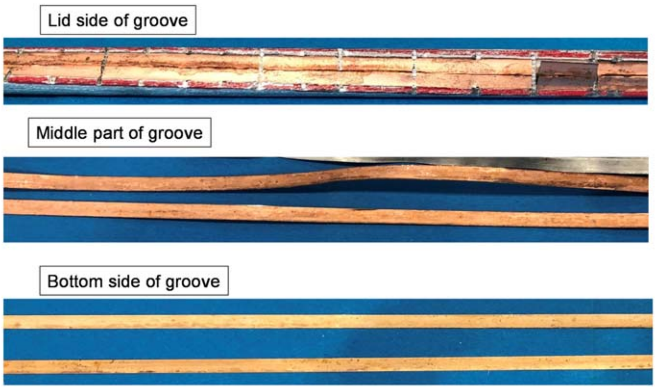

Figure 13. Check the state of REBCO tapes in the conductor that was markedly deteriorated (1 rotation/m, No. 2).

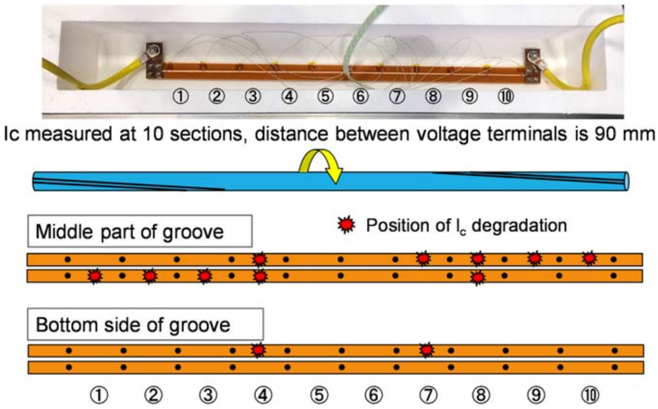

Figure 14. Position of I_c degradation of REBCO tapes (1 rotation/m, No. 2).

4.2. Improvement and second trial production

Next, we made improvements from the first trial to the second trial production. We improved the thickness and accuracy of pure aluminum sheets. To reduce the impact of FSW on REBCO tapes, we changed the size and shape of FSW tool and reduced FSW aluminum stirring area as shown in figure 15.

The normalized critical current of the second trial production of the FAIR conductor is presented in figure 16. The critical current of the non-rotating conductor decreased by less than 20%, and the progress of degradation due to thermal cycling was also observed. The degradation of the REBCO tapes is measured using voltage terminals with interval of 90 mm as shown in figure 17. The degradation of critical current is observed in the REBCO tapes at multiple locations. The decrease in critical current at each degradation point is not significant. However, when quenching occurred near critical current, the REBCO tape burned out. Consequently, it is considered that even when the degradation of critical current is small, the REBCO layer is either delaminated or sheared.

4.3. Third trial production and successful improvement

It can be observed from the cross section of the non-rotating conductor, shown on the left side of figure 18, that there are sections where the FSW is incomplete in the longitudinal direction. Therefore, the shape of the FSW tool was reviewed again and improved so that the section with incomplete FSW could not be produced.

Finally, surprising results are observed for the 1 rotation/m conductor as presented in figure 19. There was no critical current degradation in the conductor and no progress of degradation due to the thermal cycling.

5. Reason of degradation of FAIR conductor

5.1. Consideration of causes of degradation

An attempt was made to produce 2 rotations/m conductor under the same FSW conditions. As shown in figure 20, a crack occurred in the FSW part of the aluminum alloy jacket. Cracks do not occur during FSW, but

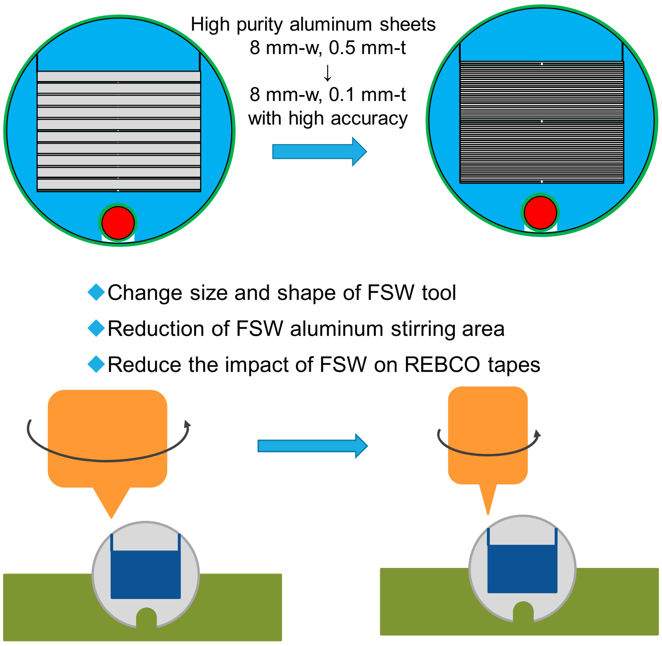

Figure 15. Improvements from first trial production to second trial production.

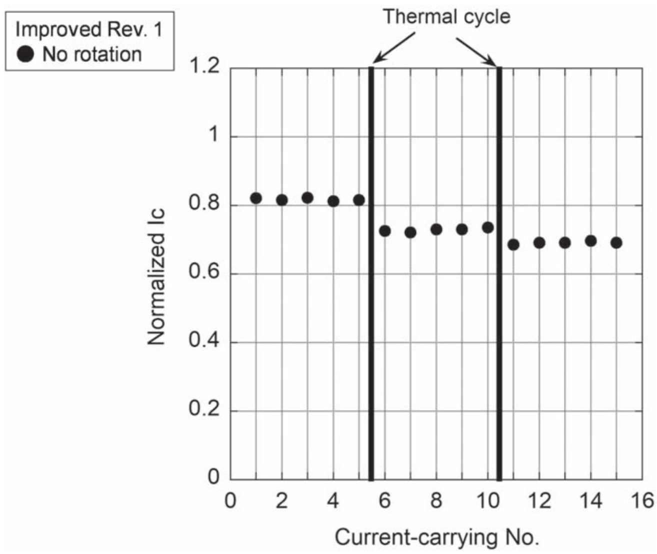

Figure 16. Normalized critical current of second trial production of FAIR conductor.

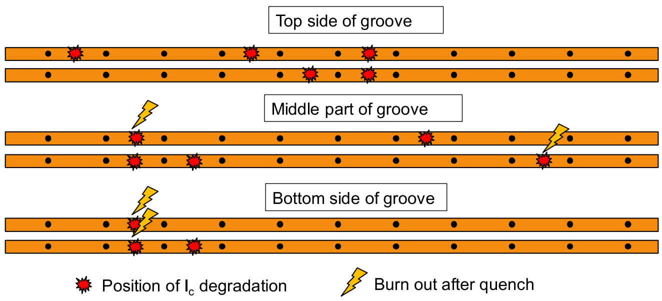

Figure 17. Check position of *Ic* degradation of REBCO tapes (second trial production).

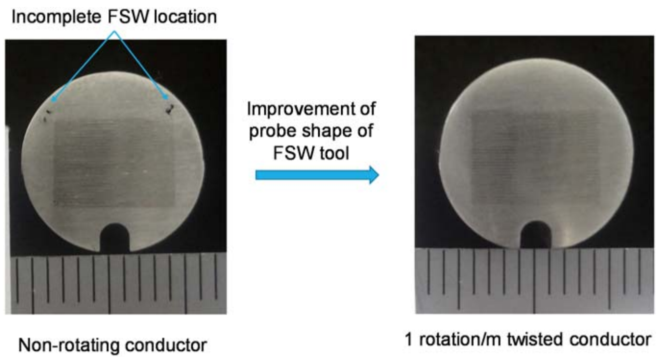

Figure 18. Improvement from second trial production to third trial production.

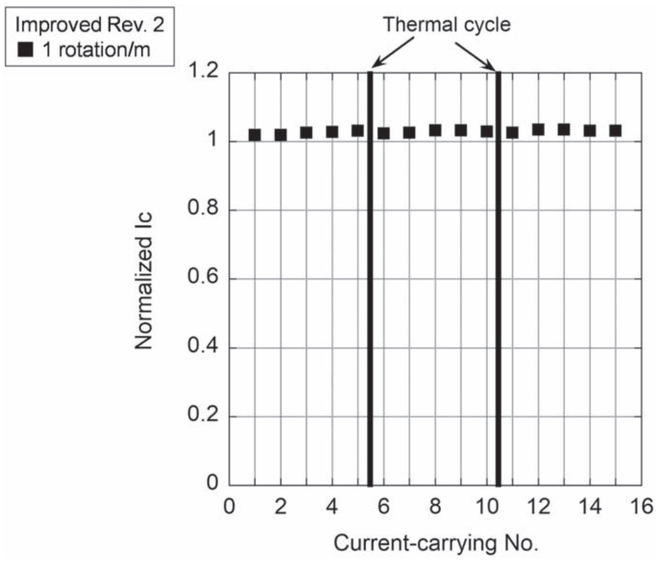

Figure 19. Normalized critical current of third trial production of FAIR conductor.

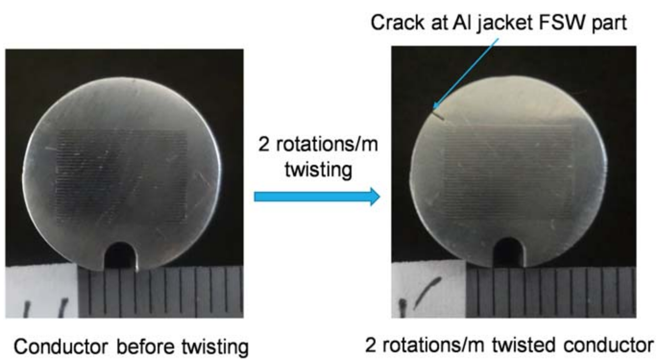

Figure 20. Aluminum alloy jacket cracking of FSW part during 2 rotations/m twisted conductor production.

the cracks were caused by insufficient strength of FSW position due to twisting the conductor. Thus, the crack length was proportional to the twisted length. It is shown that the FSW condition still has scope for improvement. FSW will be optimized, and a conductor that does not deteriorate its critical current even when twisting 2 rotations/m is planned.

By analysing the experimental results of the FAIR conductors, the causes of the critical current degradation in the conductors are determined, as detailed in figure 21. If homogeneous FSW was not performed in the

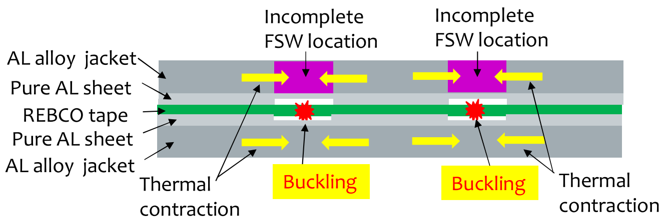

Figure 21. Reason of the critical current degradation of the FAIR conductor.

longitudinal direction of the conductor, there was a section where the REBCO tape was pinned firmly and a section where it was not constrained alternately. When the conductor cooled down to the liquid nitrogen temperature (77 K, −196 °C) from the FSW temperature (473 K, 200 °C) owing to thermal contraction, the difference in the thermal shrinkage between the aluminum alloy jacket and the REBCO tape (−0.4%) was locally applied to a section of the REBCO tape. It was estimated that excessive shear strain (buckling) was appended to the REBCO tape.

5.2. Preventive measures against deterioration

By conducting a uniform FSW in the FAIR conductor in longitudinal direction, it was confirmed by experiments that the critical current degradation did not occur in REBCO tapes even during the conductor production (including twisting) and thermal cycling. By further quantitatively evaluating the cause of REBCO conductor degradation, it has been determined that stable fabrication of FAIR conductors without critical current degradation is possible.

6. Summary

We began our research on the development of a high-current REBCO conductor (FAIR conductor) with the aim of applying it to the next experimental device of LHD. We identified the cause of the critical current degradation of the REBCO conductor. By achieving certain minor improvements in the FSW condition, a 2 rotations/m FAIR conductor without the critical current deterioration is possible. Next, the prospects have been obtained for the production of FAIR conductors without the critical current degradation. We are planning the current carrying tests on bent short-length conductors in liquid nitrogen, short-length conductor tests at 20 K, 9 T in the split magnets, and long-length conductor tests at 20 K, 13 T in the solenoid magnet. Development plan of the FAIR conductor will complete in 3 years.

We obtained important knowledge to investigate the causes of degradation of REBCO conductors and REBCO coils.

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