

Improvement of I_c degradation of HTS conductor (FAIR conductor) and FAIR coil structure for fusion device

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Abstract— As a high-temperature superconducting (HTS) conductor with a large current capacity applicable to a nuclear fusion experimental device, REBCO ($\text{REBa}_2\text{CuO}_x$) tapes and high-purity aluminum sheets are alternately laminated, placed in a groove of an aluminum alloy jacket having a circular cross section, and the lid is friction-stir welded. To make the current distribution and mechanical characteristics uniform, the conductor is twisted at the end of the manufacturing process. In the early prototype conductor, when the I_c was measured in liquid nitrogen under self-magnetic field conditions, I_c degradations were observed from the beginning, and the characteristic difference between the two prototype samples under the same manufacturing conditions were large. Furthermore, I_c degradation was progressed by repeating the thermal cycle from room temperature to liquid nitrogen temperature. This I_c degradation did not occur uniformly in the longitudinal direction of the conductor but was caused by local I_c degradation occurring at multiple locations. If the conductor was not manufactured uniformly in the longitudinal direction, the difference in thermal shrinkage between the REBCO tape and the aluminum alloy jacket caused local stress concentration in the REBCO tape and buckling occurred. Element experiments to explain this mechanism were conducted to clarify the conditions under which I_c degradation due to buckling occurs. Then prototype conductors were tested with improved manufacturing methods, and as a result, I_c degradation could be suppressed to 20% or less. We have achieved the prospect of producing a conductor with uniform characteristics in the longitudinal direction.

Index Terms—Fusion device, HTS magnet, REBCO, FAIR conductor

I. INTRODUCTION

WE have been conducting research and development on HTS conductors and coils with large current capacities applicable to the fusion experimental device. The goal is to

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achieve both high stability and high current density by taking advantage of the characteristics of HTS, and to enable safe coil operation. Superconducting magnets for a fusion device require a conductor with a large current capacity because the magnetic stored energy must be extracted outside the winding during coil quench, and many types of HTS conductors have been developed in the world [2-7]. In conventional low-temperature superconducting (LTS) conductor, round wires are twisted and assembled to increase the current capacity. However, it is difficult to assemble and increase the current with thin REBCO tapes. Furthermore, it has been reported that the REBCO tapes are locally degraded during conductor or coil fabrication, which makes it difficult to realize a large current HTS conductor.

II. FIRST AND SECOND PROTOTYPE FAIR CONDUCTOR

REBCO tapes are laminated with a high-purity aluminum sheet sandwiched between them as a cushioning material, placed in a groove of an aluminum alloy jacket having a circular cross section, and the lids are joined by friction stir welding. To make the current distribution and mechanical characteristics uniform, the conductor is twisted at the end of the manufacturing process as shown in Fig. 1. The FAIR conductor derives its name from the processes and materials used in its development: friction stir welding (FSW), aluminum alloy jacket, indirect cooling, and REBCO tapes.

I_c deterioration of the first prototype conductor, the estimation of its cause, and the improvement in the second prototype conductor were described in detail in [8]. This paper describes further improvements that followed. We also describe the results of element experiments to clarify the conditions under which I_c degradation due to local buckling of REBCO tapes occurs. To assist in the explanation in this paper, the following is a summary of what occurred in the manufacturing and testing process of the first prototype conductor and the second prototype conductor.

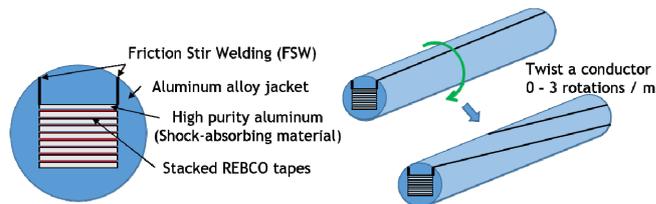


Fig. 1. Configuration of FAIR conductor

A. I_c degradation of the first prototype FAIR conductor

For the first prototype FAIR conductors, two rows of REBCO tapes with a width of 4 mm and a thickness of 0.1 mm are arranged side by side, and 10 layers are laminated with a 0.5 mm thick and 8 mm width high-purity aluminum sheet that serves as a mechanical cushioning material when the conductor is twisted. During the prototype manufacturing, only 6 REBCO tapes were used on the upper, middle, and lower sides in the groove of 8 mm width and 6 mm depth, and dummy tapes made of stainless-steel were used for the other parts instead of REBCO tapes. Multiple short sample conductors with a length of 1 m and an outer diameter of 12 mm were prepared by changing conductor twist pitches.

I_c measurements were performed in liquid nitrogen and self-field condition, 11 times on each sample, with two thermal cycles to room temperature and liquid nitrogen temperature in between. The purpose of the experiment was to clarify the conditions under which I_c of the FAIR conductor does not degrade when the conductor is twisted. As for the degradation of the obtained I_c , the characteristic difference between the two conductors manufactured under the same conditions was larger than the influence of the twist pitch, and the influence of the twist pitch could not be quantitatively evaluated.

B. I_c improvement of the second prototype FAIR conductor

To improve the manufacturing accuracy of the conductor, the thickness of the high-purity aluminum sheet was reduced to 0.1 mm, which is the original design value of the conductor, and the manufacturing accuracy such as thickness and width were improved. During the prototype testing, only 6 REBCO tapes were used on the upper, middle, and lower sides of the groove. Here, by inserting all 60 REBCO tapes as designed, a large current capacity conductor of 12.5 kA can be constructed at a temperature of 20 K and a magnetic field of 12 T.

Since it was clarified that the FSW conditions for welding the aluminum alloy jacket lid greatly affect the I_c degradation characteristics of the conductor, the FSW tool shape, welding conditions, etc., were optimized. In the change from the first FSW tool shape to the second tool shape, the diameter of the shoulder part of the FSW tool was reduced in order to reduce the range in which FSW affects the I_c degradation of the conductor. Fig. 2 shows the change of the cross-section from the first to the second prototype FAIR conductor.

Fig. 3 shows the results of all prototype I_c measurements. In the normalized I_c of the second prototype conductor, the deg-

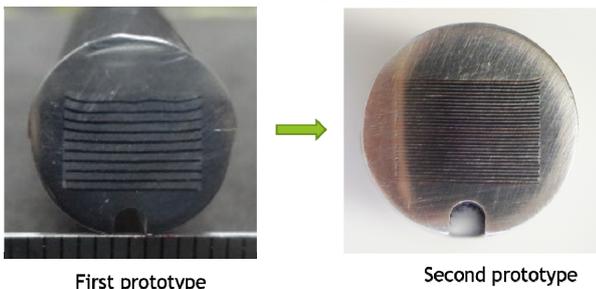


Fig. 2. Change of cross-section from first to second prototype FAIR conductor

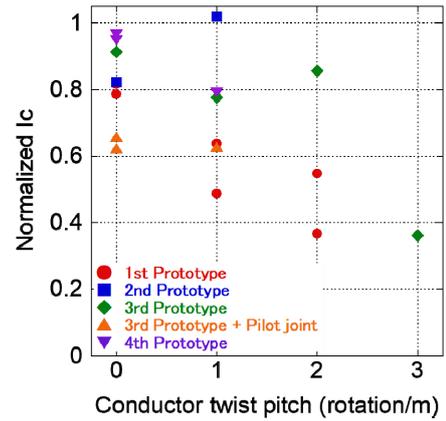


Fig. 3. Normalized I_c measurement of all prototypes of FAIR conductor

radation of I_c was suppressed to 20 % or less, and the result of 1 rotation/m twist sample was obtained without any degradation of I_c . However, when a twist of 2 rotations/m was applied under the same conditions, cracks occurred in the FSW part, and it became clear that further optimization of the FSW conditions was necessary.

III. THE CAUSE OF I_c DEGRADATION AND ELEMENT EXPERIMENTS

The cause of the I_c degradation in the FAIR conductor is that if uniform FSW is not performed in the longitudinal direction of the conductor, there will be a part where the REBCO tapes are locally firmly fixed and a part where they are not restrained. Due to the difference in thermal shrinkage between aluminum alloy and REBCO tape during cooling from the average conductor fabrication temperature to the liquid nitrogen temperature (423 K \rightarrow 77 K), excessive compressive strain is locally applied to the REBCO tape. It was presumed that the REBCO tapes buckled at these positions. For elemental experiments and analysis results showing that the difference in thermal shrinkage between the REBCO tape and the aluminum alloy jacket causes local stress concentration in the REBCO tape, resulting in buckling, which is the cause of I_c degradation.

Fig. 4 shows the setup of the element experiment of I_c degradation due to thermal shrinkage. Place the REBCO tape on the aluminum alloy lower fixture and sandwich it with the aluminum alloy upper fixture with a length L groove that becomes a local non-restraint. When cooled from the reference temperature to the liquid nitrogen temperature, the different thermal shrinkage rates of the aluminum alloy and the REBCO tape cause local stress concentration in the REBCO tape in unrestrained space L . Here, the length L of the unrestrained part can be changed by 0.5 mm from 1 mm to 4 mm. In order to change the thermal stress due to cooling from the reference temperature to the liquid nitrogen temperature of 77 K, I_c measurement was performed under two conditions, one when the reference temperature was 300 K and the other when the reference temperature was 423 K. To compare the case where



Fig. 4. Element experiment setup that simulate I_c degradation due to thermal shrinkage

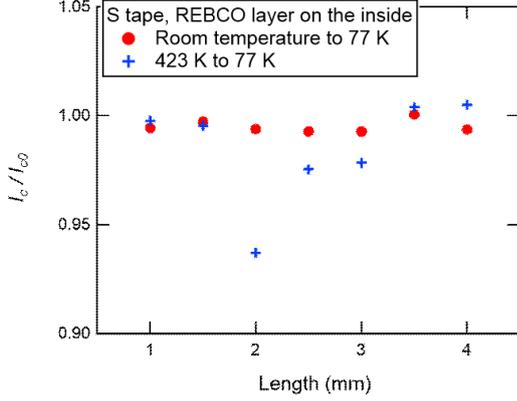


Fig. 5. Relationship between normalized I_c and local groove length in the direction of compression applied to the REBCO layer

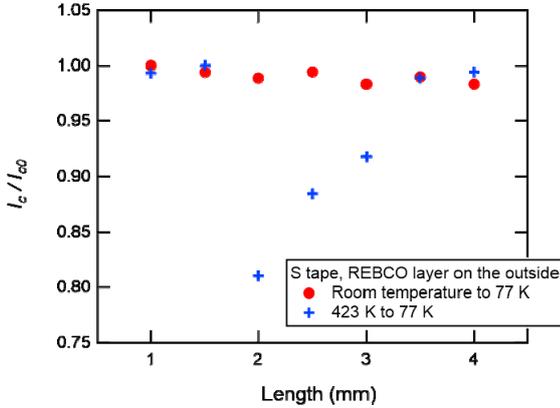


Fig. 6. Relationship between normalized I_c and local groove length in the direction of tension applied to the REBCO layer

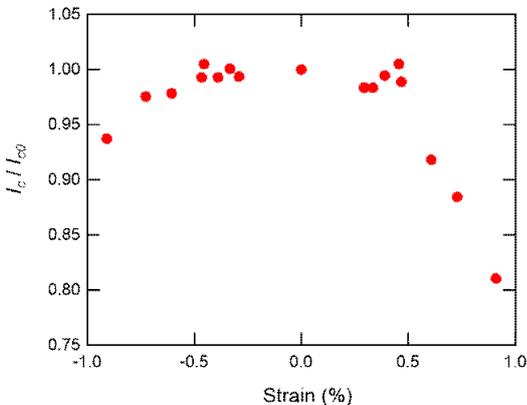


Fig. 7. I_c degradation with the horizontal axis converted to strain due to thermal shrinkage

buckling occurs inside the REBCO layer and the case where it

occurs outside, the front and back sides of the REBCO tape were arranged separately. In Fig. 4, the REBCO layer faces the lower aluminum alloy jacket on the inside, and the upper layer faces the outside. On the inside, compressive stress is applied to the REBCO layer. On the contrary, in the case of the outside, tensile stress is applied.

Fig. 5 shows the I_c characteristics when the REBCO layer is arranged inside so that compression is applied to the REBCO layer. Fig. 6 shows the I_c characteristics when the REBCO layer is arranged on the outside so that tension is applied to the REBCO layer. In both Figs. 5 and 6, when the reference temperature was 300 K, I_c degradation was not observed regardless of the length L . At the reference temperature of 423 K, it degraded as it decreased from $L = 4$ mm, and showed the maximum degradation at $L = 2$ mm. However, when $L = 1.5$ mm, I_c degradation did not occur, and even when $L = 1$ mm, no degradation occurred. When the REBCO tape was placed inside as shown in Fig. 5, $L = 2$ mm resulted in 7% I_c degradation, and when placed outside of Fig. 6, $L = 2$ mm resulted in 19% I_c degradation. The reason why I_c degradation does not occur when $L < 2$ mm is considered to be that the stress required for buckling increases as the unconstrained distance decreases.

Buckling causes the REBCO tape to bend, causing I_c degradation at that point. The shape of bending due to buckling was approximated by a sine wave, and the bending strain was calculated from the length of the unconstrained region. Fig. 7 shows the results of reorganizing Figs. 5 and 6 by converting the horizontal axis into the bending strain of the REBCO tape. Quantitative results were obtained that I_c degradation progresses as the absolute strain increases. In addition, the results consistent with the previous study [9] on the bending characteristics of REBCO tapes, which said that I_c degradation is more likely to occur due to tensile strain than to compressive strain, were obtained.

IV. FURTHER IMPROVEMENTS OF FAIR CONDUCTOR

A. Third and Third+P.J. prototype FAIR conductor

In the third prototype improvement, the shape of the pin part of the FSW tool was thickened from the second prototype so that a stronger FSW can be performed. As shown in Fig. 3, it was confirmed that the I_c degradation of the third prototype was observed about 20%. However, the I_c characteristics did not change until the conductor twist pitch of 0 to 2 rotations/m, and the I_c became less than 40% with the twist pitch of 3 rotations/m. It was presumed that this was due to the irreversible distortion of the FAIR conductor due to the 3 rotations/m of the twist pitch. The third prototype was improved by introducing the pilot joint (P. J.) FSW (FSW in which the outside of the welding line is performed with a thin tool before the main welding) for the purpose of increasing the uniformity of the FSW in the longitudinal direction of the conductor. As a result, strong FSW became possible, but the residual stress applied to

the REBCO tape during the conductor production increased, resulting in about 40 % I_c degradation as shown in Fig. 3.

B. Fourth prototype FAIR conductor

Fig. 8 shows the change in the shape of the groove where the laminated REBCO tapes are inserted in the FAIR conductor. Before producing the first prototype, FSW with less deformation of the groove was made. However, after the third+P.J. prototype, a large deformation occurred in the groove, and as a result, excessive residual stress was applied to the REBCO tapes. In the upper left of Fig. 8, the cross section of the before first prototype shows the groove shape in the final conductor shape of the circular cross section. In the lower center of Fig. 8, the cross section of after the third prototype + P.J. shows the shape of the groove and the flat upper lid is attached to the lower part of the aluminum jacket with a circular cross section by FSW and then the upper surface is machined to form a conductor with a circular cross section.

Before manufacturing the fourth prototype, the FSW conditions were readjusted and improvements were made to reduce the deformation of the groove. In the upper right of Fig. 8, before the 4th prototype, to adjust the conditions of FSW, the shape change of the groove after FSW was observed with a plate-shaped test sample at both the lower and the upper parts of the aluminum jacket. In the fourth prototype, the FSW tool shape was returned to the second shape and P. J. was added to optimize the FSW conditions and to optimize to reduce the residual stress applied to the REBCO tape. As a result, it was possible to produce a sample with I_c degradation suppressed to 20 % or less as shown in Fig. 3.

V. CONDUCTOR N VALUE AND I_c DETERIORATION

It was clarified that the cause of I_c degradation was not a homogeneous I_c decrease over the entire length of the conductor, but a local degradation occurring at multiple locations on the conductor. As data to support this, Fig. 9 in which the n value of the produced samples was measured is shown. In the prototypes of the first and the third+P.J., where the degradation was large, the decrease in n value was also large. As shown in Fig. 10, there is a clear correlation between the n value and I_c degradation. The worse the I_c , the lower the n value. It is necessary to maintain the n value at 15 or more to

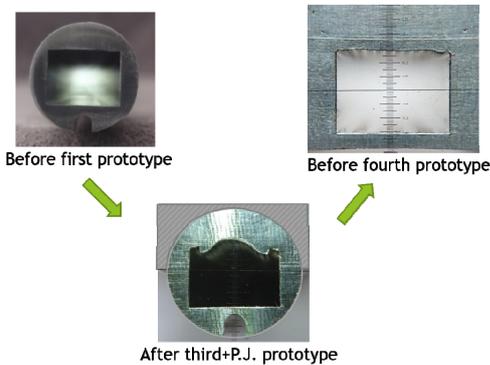


Fig. 8. Conductor groove shape changes from first to third+P.J. prototype

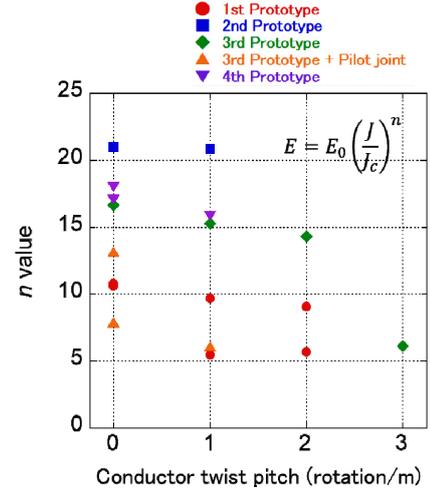


Fig. 9. Change in n value for each prototype sample

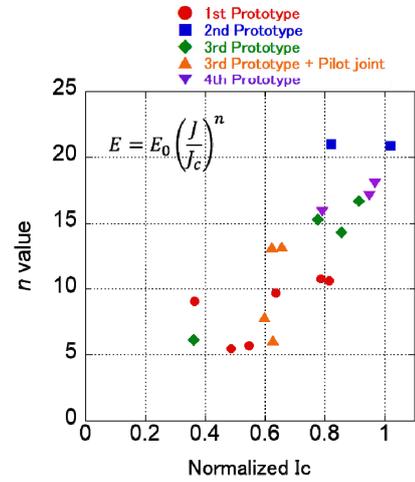


Fig. 10. Relation between n value and normalized I_c

suppress the I_c degradation to 20 % or less.

VI. SUMMARY

We have started R&D of a large current HTS conductor (FAIR conductor) aiming at application to fusion experimental device. Degradation of I_c was observed in the early conductor prototypes. It was clarified that the I_c degradation of the conductor due to the local buckling of the REBCO tapes. The local buckling occurred by thermal shrinkage during cooling from the conductor fabrication temperature to the liquid nitrogen temperature. By optimizing the FSW conditions during conductor production and eliminating non-uniformity in the longitudinal direction of the conductor, we were able to produce a FAIR conductor with I_c degradation less than 20 %. As a next step, we are planning to conduct an excitation test of FAIR conductors in a magnetic field under variable temperature conditions to confirm its performance.

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