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Development of Ta-matrix Nb_3Al Strand and Cable for High-Field Accelerator Magnet

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***Abstract*—Research and development of Nb_3Al strands and cables for a high field accelerator magnet is ongoing under the framework of the CERN-KEK collaboration. In this program, new Ta-matrix Nb_3Al strands were developed and their mechanical properties and superconducting properties were studied. The non-Cu J_c values of these strands were $750 \sim 800$ A/mm^2 at 15 T and 4.2 K. Using these strands, test fabrication of 27-strand Rutherford cable was carried out in collaboration with NIMS and Fermilab. The properties of the strands extracted from the cable were examined and it was found that there was no degradation of the superconducting properties of the strands. In this paper, we report the fabrication of the strands and the cable in brief and present some of the results obtained by studying their properties.**

***Index Terms*—Critical current, magnetization, Nb_3Al wire, Rutherford cable, tensile strength, Vickers hardness.**

I. Introduction

Nb_3Al wires processed by rapid heating, quenching and transformation (RHQT) [1] have better strain and stress tolerances [2], [3] and exhibit promising high-field J_c properties as compared to Nb_3Sn wires. Therefore, an RHQT-processed Nb_3Al wire can be a promising candidate for use in next-generation high-field accelerator magnets. For many years, we have been working on the development of the Nb_3Al wires. In the course of this development, we found that the Nb_3Al wire exhibits rather strong magnetic instability in a low field when Nb is used as a matrix material [4]. In order to suppress this instability, we have been developing Ta-matrix wires with a matrix ratio of 0.8 [5]. During the fabrication of the precursor wire, breakage occurred several times; nonetheless, we were finally able to fabricate a copper-stabilized Ta-matrix Nb_3Al strand with length of approximately 270 m. This strand was used to carry out test fabrication of a 27-strand Rutherford cable at Fermilab.

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TABLE I
Main Parameters of Precursor and Final Strand

	Precursor	Final strand
Matrix material	Ta	Ta
Matrix ratio	0.8	0.8
Wire diameter (mm)	1.29	1.0 with Cu (0.715 w/o Cu)
Filament diameter (μm)	70	37
Filament spacing (μm)	8	4.2
Number of filaments	222	222
Twist pitch (nm)	0	45

II. Strand Details

A. Fabrication of Strand

A multifilament precursor wire with a Ta matrix was manufactured by the conventional jelly-roll process at Hitachi Cable, Ltd. The starting monofilament wire was prepared by rolling Nb and Al foils around a Ta core and wrapped with Ta foils, which eventually becomes a barrier between adjacent filaments. This process was followed by extrusion and drawing. These monofilament wires and the Ta core wires were assembled together and wrapped with a Ta sheet, after which, they were stacked into a multifilament billet with a diameter of approximately 60 mm.

The billet was then extruded and drawn to a wire with a diameter of approximately 1.35 mm. During this process, wire breakage occurred several times in spite of the fact that the billet was encased in a Cu-Ni sheath for carrying out the size reduction smoothly. After this drawing process, the Cu-Ni sheath was etched off for the RHQ treatment and the wire diameter was measured. Since the variation in the diameter was relatively large, a die drawing process was applied to the precursor wire to reduce the size variation. The main parameters of the precursor wire are listed in Table I.

A precursor wire with a diameter of 1.29 mm was then subjected to the RHQ treatment. Fig. 1 shows the RHQ current and voltage during the treatment. Although the current was maintained almost constant, the voltage changed at some place along the wires. In order to investigate the reason for these voltage changes, we compared the variation in the wire diameter and in the RHQ voltage, and found that there is a correlation between two. When the wire diameter changed by approximately 10 μm, the RHQ voltage changed approximately 1 V. This implies that

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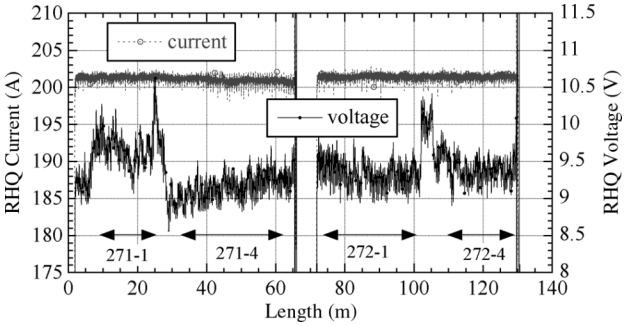

Fig. 1. Traces of current and voltage across the electrodes during the RHQ treatment.

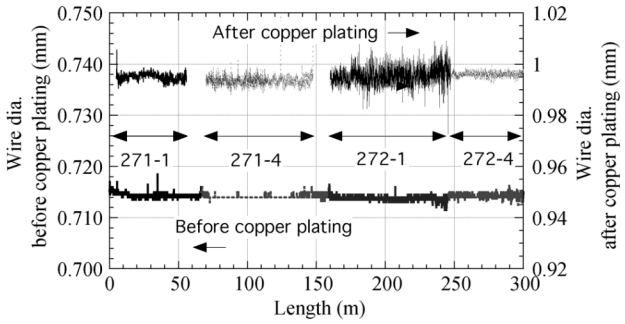

Fig. 2. Strand diameters before and after copper plating.

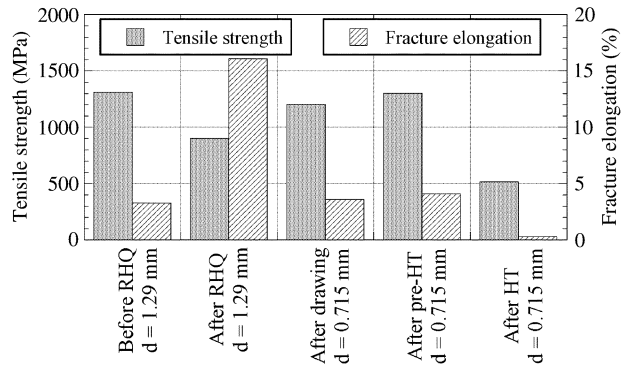

Fig. 3. Tensile strengths and fracture elongations of wires at various fabrication steps.

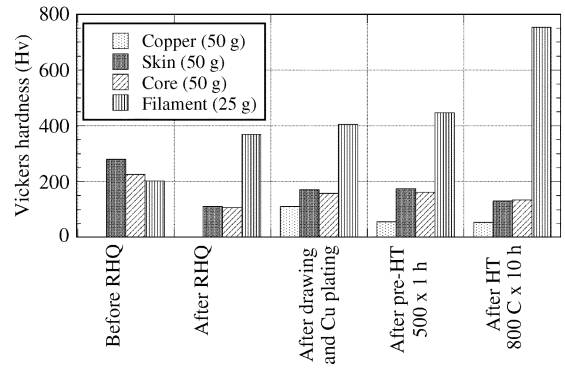

Fig. 4. Vickers hardness at various regions across the cross section of wires at various fabrication steps. The load applied to measure the hardness of the filament was 25 g, while that for other regions was 50 g.

the energy density of the RHQ treatment changes by roughly 10% and hence, the temperature of the RHQ treatment will change by approximately 100°C. This is a fairly large change that will influence the superconducting properties of the Nb_3Al strand; therefore, the wire was divided into four pieces (strands 271-1, 271-4, 272-1, and 272-4) as shown in Fig. 1 to remove the portions with unstable RHQ treatment. Subsequently, the wires were drawn down to approximately 0.75 mm in diameter, twisted with a pitch of 45 mm, and then adjusted in diameter by a final die drawing. Copper was then electroplated onto the surface of the wires.

Fig. 2 shows the diameters of the strands before and after copper plating. The strand diameters, which were continuously measured by a laser micrometer, were very well controlled before copper plating (the standard deviation of the diameter was approximately 0.4 μm), and were fairly well controlled even after copper plating (the standard deviation was approximately 1 μm). The relatively large variation in the diameter of strand 272-1 after copper plating might be attributed to the noise of the measurement system.

B. Mechanical Properties

To investigate the mechanical properties of the Nb_3Al wires at various stages of the fabrication process, tensile tests and Vickers hardness measurements were performed at room temperature.

Fig. 3 shows the tensile strength and the fracture elongation of the wires and how the mechanical properties of the wires change through the fabrication steps. The fabrication process proceeds from left to right in the figure. Just before RHQ treatment, the precursor wire has the largest tensile strength and the smallest elongation in the samples, with the exception of the heat-treated sample. This is a result of the hard processing during fabrication that must be accomplished without annealing. As a result of the RHQ treatment, the wire becomes soft and shows large elongation; however, the wire becomes hard again after the wire drawing process. The effect of the pre-heat treatment, whose temperature was around 500°C, is not so clear. After heat treatment to transform the filament material (bcc phase) into the A15 phase, the wire becomes very brittle and the fracture elongation becomes extremely small.

The Vickers hardness was also measured at various regions across the cross section of the wires whose tensile strength and fracture elongation are shown in Fig. 3. The results are shown in Fig. 4. In the precursor wire just before the RHQ treatment, the hardness values of three regions (skin, core and filament) are more or less equal, even though the values are fairly large ($\mathrm{Hv} = 200 \sim 300$). After the RHQ treatment, the skin and core become soft, however, the filaments become hard because the Nb/Al in the filament is converted into the bcc phase. The drawing process after the RHQ treatment slightly increases the hardness of all the parts of the wire. After the transformation heat treatment, the hardness of the filament portion increases dramatically because of the A15 phase. Results of the tensile tests and the Vickers hardness measurements are in good agreement with each other.

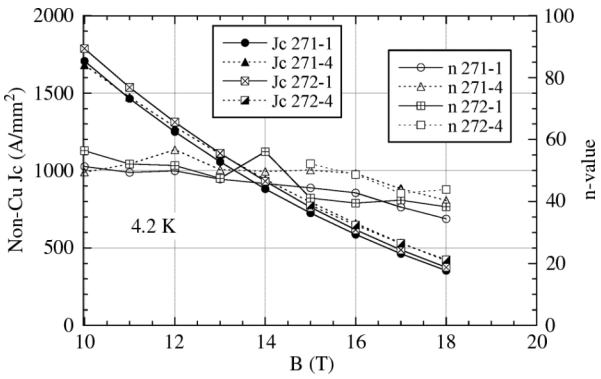

Fig. 5. Non-Cu J_c and n-value of four types of strands used for cable fabrication. All strands were heat treated at 800°C for 10 h.

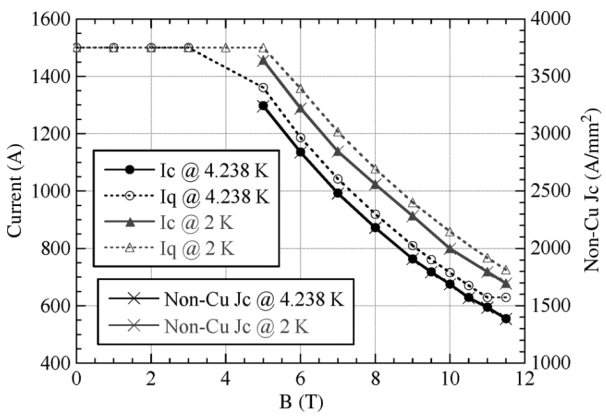

Fig. 6. Critical current and quench current versus field for strand 271-4 at 4.2 K and 2 K. This measurement was performed at BNL.

C. Superconducting Properties

The critical current (I_c) of the strand at 4.2 K was measured as a function of the field. The criterion of I_c used in this study was 20 $\mu\mathrm{V/m}$. The estimated uncertainty in the I_c measurements was less than $\pm 5\%$. The n-values of the samples were determined in the 10–40 $\mu\mathrm{V/m}$ range by fitting the V-I curve with the power law $\mathrm{V} \sim \mathrm{I}^{\mathrm{n}}$.

Fig. 5 shows the non-Cu J_c and the n-value of the four types of strands shown in Figs. 1 and 2. The results of these strands are very similar. The average non-Cu J_c at 15 T and 4.2 K is 765 $\mathrm{A/mm^2}$, and variations in J_c between these strands is fairly small, i.e., approximately $\pm 5\%$. The n-values of these strands are also very similar.

In addition to these I_c measurements at 4.2 K, a study of low field instability [4] at 4.2 K and 2 K was performed at the Brookhaven National Laboratory, where the I_c and I_q were measured in the field range of 0 T to 11.5 T. Fig. 6 shows the results of this study. The plateau of the I_q plot below 5 T is due to the current limit of the power supply for these measurements. We cannot see any indication of low field instability at 4.2 K or even at 2 K.

In order to further investigate the effect of the Ta matrix on the Nb_3Al strand, magnetization measurements were also performed as a function of field by using a Quantum Design SQUID magnetometer. Approximately 4-mm long samples were used for the measurements. The results are shown in Fig. 7. The M-B curve at 4.4 K is very smooth and flux jumps are not observed. However, tiny flux jumps are observed in the low field region at 2 K. These jumps might originate in and be limited to the surface region of the strand. At present it is unclear whether any problem related to these tiny flux jumps will be encountered in accelerator magnet applications.

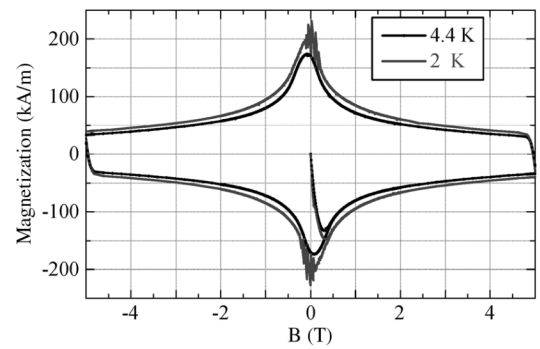

Fig. 7. Magnetization of strand 272-4 as a function of field at 4.4 K and 2 K.

TABLE Ii
MAIN PARAMETERS OF RUTHERFORD CABLE

Cable width (mm)	13.93
Cable thickness (mm)	1.84
Number of strands	27
Strand lay angle (deg)	14.5
Packing factor (%)	85

Fig. 8. Cross-section of a 27-strand Rutherford cable.

III. RUTHERFORD CABLE

A. Fabrication of Cable

Test fabrication of a 27-strand Rutherford cable was carried out using a compact cabling machine at the Fermilab. The total length of the strands prepared for the cabling was approximately 260 m; the following four types of strands were used: 271-1, 271-4, 272-1, and 272-4, as shown in Figs. 1 and 2. Approximately 8-m long cable was made from the strands. The main parameters of the cable are listed in Table II. A cross-sectional photograph of the cable is shown in Fig. 8. A closer inspection of this photograph reveals many separations between the copper stabilizer and the Nb_3Al strand. This indicates that the bonding strength between the copper stabilizer and the Nb_3Al strand is not enough for cabling work and that further improvement of the bonding strength is necessary for future cables.

B. Critical Current Measurement of Extracted Strand

In order to examine the degradation of the strand performance due to the cabling work, the I_c values of the strands extracted from the cable were measured. Approximately 400-mm long strands were extracted from the cable and the kinked portions

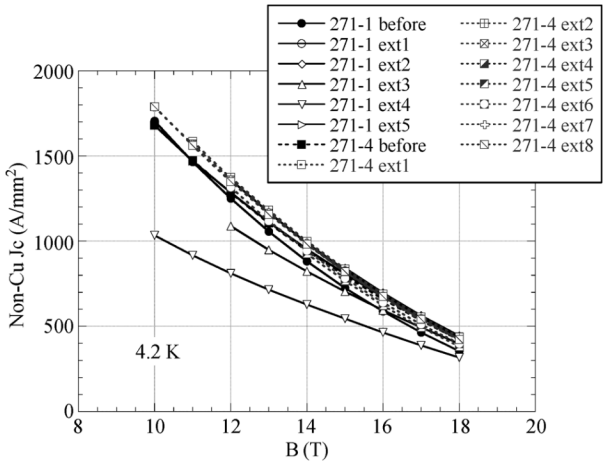

Fig. 9. Non-Cu J_c of the strands 271-1 and 271-4, extracted from the Rutherford cable. Data of the strands before cabling are also shown for comparison.

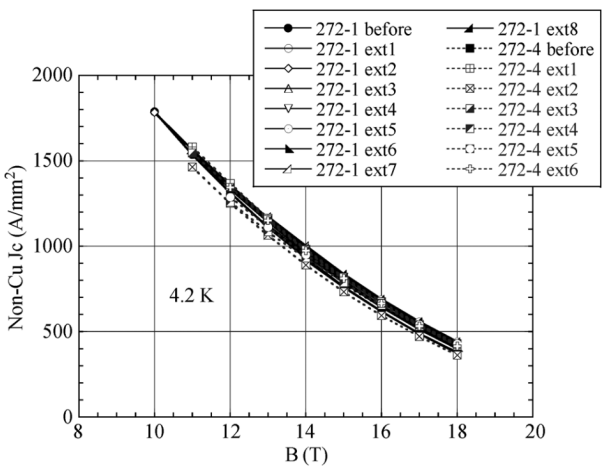

Fig. 10. Non-Cu J_c of the strands 272-1 and 272-4, extracted from the Rutherford cable. Data of the strands before cabling are also shown for comparison.

were straightened; the strands were then wound on a stainless steel cylinder and heat treated at 800°C for 10 h. Subsequently, the strands were mounted on an I_c measurement holder. The voltage tap distance used for determining the I_c was 150 mm, in which three straightened portions were included. The non-Cu J_c of all the strands are plotted as a function of the field in Figs. 9 and 10. From these figures, the following points become clear: (1) the width of scatter in the non-Cu J_c for each group of the extracted strands are fairly narrow (approximately $\pm 5\%$ at 15 T), except for group 271-1; (2) degradation of J_c due to the cabling work is not observed; and (3) the average non-Cu J_c values at 4.2 K for all the extracted strands are 1290 $\mathrm{A/mm^2}$ and 793 $\mathrm{A/mm^2}$ at 12 T and 15 T, respectively.

In order to identify the reason for the rather large spread of the J_c for group 271-1 in Fig. 9, we reviewed various fabrication parameters. We suggest that a possible reason might be the relatively large fluctuation in the RHQ voltages during the RHQ treatment for the strands in the group 271-1. This can be observed in Fig. 1.

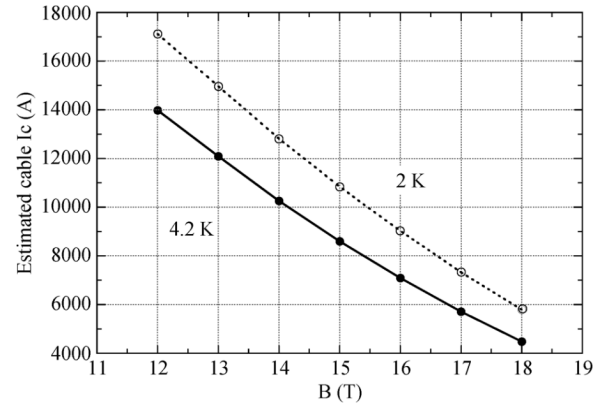

Fig. 11. Estimated critical current of the 27-strand Rutherford cable.

Fig. 11 plots the I_c of the fabricated cable, which was estimated from the I_c values of the extracted strands.

IV. Conclusion

A Ta-matrix $\mathrm{Nb_3Al}$ strand was newly fabricated, and a trial fabrication of a 27-strand Rutherford cable was carried out using the strand. The main results of this study are summarized as follows. (1) Although the fabrication of the precursor wire was carefully carried out, wire fracture occurred several times, indicating that further improvement in the workability of the Ta-matrix precursor wire was necessary to increase the yield ratio of its fabrication. (2) Fabrication of a 27-strand Rutherford cable could be carried out rather smoothly without serious problems, although the cable cross section revealed separation of the copper stabilizer from the $\mathrm{Nb3Al}$ wire. (3) Degradation of the superconducting properties due to the cabling work was not observed in the strands extracted from the cable, whose packing factor was 85%. (4) At 15 T and 4.2 K, the average non-Cu J_c of the extracted strand was 793 $\mathrm{A/mm^2}$ and the estimated I_c of the cable was 8600 A.

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References

[1] T. Takeuchi *et al.*, "Status and perspective of the $\mathrm{Nb3Al}$ development," *Cryogenics*, vol. 48, pp. 371–380, 2008.

[2] N. Banno, D. Uglietti, B. Seeber, T. Takeuch, and R. Flukiger, "Strain dependence of superconducting characteristics in technical $\mathrm{Nb3Al}$ superconductors," *Supercond. Sci. Technol.*, vol. 18, pp. 284–288, 2005.

[3] A. Kikuchi *et al.*, "Cu stabilized $\mathrm{Nb3Al}$ strands for the high field accelerator magnet," *IEEE Trans. Appl. Superconductivity*, vol. 18, no. 2, pp. 1026–1030, 2008.

[4] A. Kikuchi *et al.*, "Characteristics of round and extracted strands of Nb3Al Rutherford cable," *IEEE Trans. Appl. Superconductivity*, vol. 17, no. 2, pp. 2697–2701, 2007.

[5] K. Tsuchiya *et al.*, "Development of Ta-matrix Nb3Al wire for next-generation accelerator magnet," *IEEE Trans. Appl. Superconductivity*, vol. 19, no. 3, pp. 2674–2677, 2009.