

Experimental Study on the Critical Current Properties of Flexible Nb₃Al Superconducting Wires in Cryocooler System

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Abstract— In recent years, Jelly-rolled Nb/Al composite monofilament Nb₃Al superconducting wires with an outer diameter of 30 μm , and multi-stranded Nb₃Al wires were successfully fabricated by NIMS in Japan. So, it is necessary to measure the temperature dependence of the critical current of Nb₃Al wires in cryocooler system for development of superconducting applications cooled by conduction cooling method. The single and multi-stranded ultrafine Nb₃Al superconducting sample wires with different outer diameter were prepared to evaluate the critical current properties. The critical currents of sample wires were evaluated by the current sweep method and constant current method. In this study, the sample wires were soldered to the copper wire to prevent burnout of the sample wire during critical current measurements. Therefore, the amount of current shunted to the copper wire was estimated to accurately evaluate the critical current of the superconducting wire. Also, the critical current of Nb₃Al wires due to bending strain (bending radius of 5 to 15 mm) was experimentally investigated. From the critical current measurement results of Nb₃Al wires with different cross-sectional structures, it was confirmed that the superconducting properties of the wires were improved by reducing the wire diameter. It was shown that the critical current density of the developed Nb₃Al wire is lower than that of REBCO wire, but higher than that of commercial NbTi and Nb₃Sn wires.

Index Terms— ultrafine Nb₃Al wire, conduction cooling, critical current characteristics, I_c measurement method

I. INTRODUCTION

Nb₃Al has better strain and stress tolerance than that of Nb₃Sn and exhibits promising high field J_c properties in the liquid helium temperature [1]–[3]. Therefore, Nb₃Al wires have the potential to be promising candidates for use in the high magnetic field applications. However, it is difficult to manufacture as a wire due to the diffusion problem between Nb/Al and Cu and the high heat treatment temperature. Jelly-rolled Nb/Al composite monofilament wires with an outer diameter of 30 μm , and multi-strand wires were successfully fabricated [4]. Since the developed Nb₃Al wire has flexibility, it is expected that a superconducting magnet can be developed by the React & Wind method. Therefore, we are planning to use this high performance Nb₃Al wires for the development of superconducting applications operated in cryocooler system. To design the superconducting applications cooled by cryocooler, it is necessary to clarify the critical properties of Nb₃Al wires

in conduction cooling conditions. In this study, ultrafine Nb₃Al superconducting single wires and stranded wires with different outer diameters and cross-sectional structures were fabricated by the Jelly-rolled method, and their critical properties were measured by conduction cooling system. The bending strain characteristics of the critical current, which is necessary to determine the bending radius of the coils, were also studied.

II. PREPARED Nb₃AL WIRES

In the early stages of the development of Nb₃Al wire using the Jelly-rolled method, Ta was used as the core material (Type A) because it does not react easily with Nb/Al during the heat treatment process. However, since Ta is mechanically hard, it was difficult to make the long length wire, so Nb was selected as the core material in the next stage (Type B). A structure without Nb barrier was proposed to further reduce the wire diameter of Nb₃Al superconducting wire (Type C). A sample wire with a copper core (Type D) was developed to realize flexible and

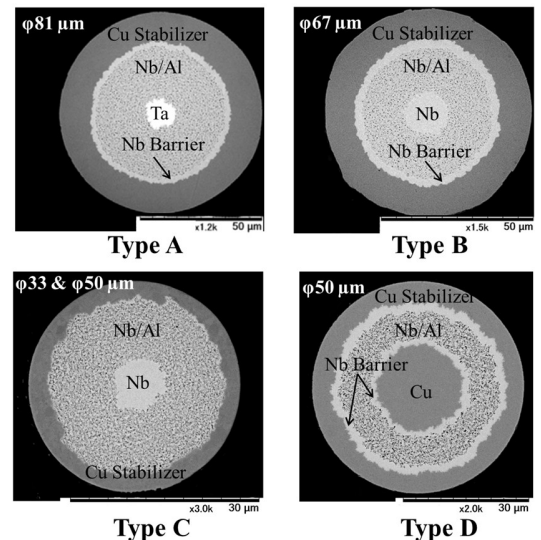


Fig. 1. The cross-sectional view of four types of Nb₃Al wires with different cross-sectional structures and wire diameters fabricated by the Jelly-rolled method.

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long length Nb_3Al superconducting wire. In the case of Type D, Nb barriers are required to suppress the reaction between Cu and Nb/Al. Fig.1 shows the cross-sectional view of Nb_3Al sample wires, and two sample wires of Type C were prepared with wire diameters of 33 μm and 50 μm . The Cu/nonCu ratio of Type C and D are 0.5 and 1, and 7-stranded Nb_3Al wires with different twist pitch (5 and 8 mm) using Type C and D were prepared. The critical current characteristics of 7-stranded Nb_3Al superconducting wires using Type A and Type B were experimentally investigated in previous study [5].

III. I_c MEASUREMENT METHODS

Fig. 2 shows the 4 K-class GM cryocooler system and sample stage to measure the critical current properties of Nb_3Al wires. The sample stage is composed of copper blocks for current leads and aluminum nitride (AlN) block. AlN plate and block were used for electrical insulation and thermal conduction. The temperature of AlN block, current lead and sample wire was measured using small size Cernox sensor (CX series). Cernox sensors were thermally contacted with APIEZON grease and then mechanically clamped to measure the sample temperature as accurately as possible.

The sample wire under conduction cooling system is adiabatic state except for the current leads. In addition, we experienced burnout of the sample wire when measuring the critical current due to the small amount of stabilizer in the sample wire. It was difficult to completely prevent burnout even when the current source was shut down using the threshold value of the voltage between taps. Therefore, in this study, the sample wires were soldered to a 1.2 mm diameter copper wire to prevent the sample wire from burning out during critical current measurements. Fig. 3 shows the measured T_c of Type D wires by 4-probe method and DC currents of 200 mA, 1 A, 2 A and 3 A. The transition to the superconducting state begins at the same temperature of 15.5 K for each current, but the transition width and residual voltage increase in proportion to the magnitude of

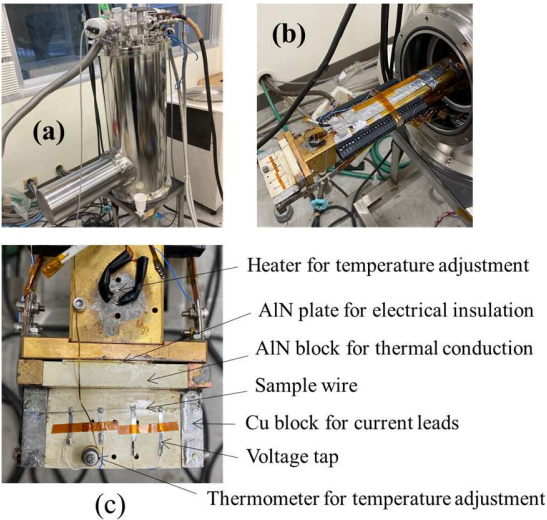


Fig. 2. Photos of (a) 4 K-class L-shaped GM cryocooler system, (b) Copper block for thermal conduction and sample stage, and (c) close-up of sample stage for critical current measurement.

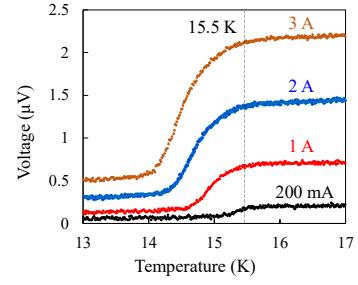


Fig. 3. Measured T_c of Type D wire by 4-probe method and DC currents of 200 mA, 1 A, 2 A and 3 A under conduction cooling.

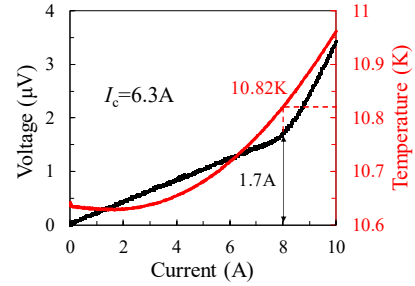


Fig. 4. The typical generated voltage between taps and temperature of sample wire when measuring the critical current by current sweep method.

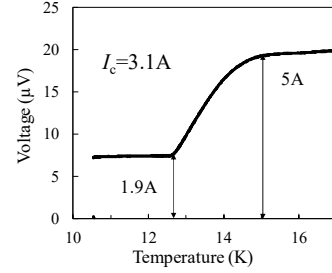


Fig. 5. The typical generated voltage between taps when measuring the critical current by constant current method and the transport current of 5 A.

the current. The difference in transition width is due to the temperature dependence of the critical current and the magnitude of the self-field, and the residual voltage indicates that current is flowing in the soldered copper wire. Figs. 4 and 5 show the typical generated voltage between taps when measuring the critical current by current sweep and constant current methods. From Figs. 3 to 5, it is found that the current is shunted to the copper wire even when the sample wire is in the superconducting state, and it can be predicted that a resistive component (contact resistance, etc.) is connected in series with the superconducting wire. Therefore, in order to determine the critical current of the Nb_3Al wires, it is necessary to know the amount of current flowing in the copper wire. To estimate the current flowing in the copper wire, we measured the electrical resistivity of the copper wire below 30 K. Fortunately, the electrical resistivity of copper wire was constant at $1.01 \times 10^{-10} \Omega \cdot \text{m}$ below 15 K. In Figs. 4 and 5, the critical currents obtained by calculating the shunt currents to the copper wires are 6.3 A and 3.1 A, respectively. When measuring the critical current under the conduction cooling system, the constant current method can be evaluated more correctly than the current sweep method if the

critical current is relatively large. In this study, the critical current of sample wires was evaluated by both the current sweep and constant current methods. In both cases, the critical current is evaluated based on the measured temperature of the sample wire during current transport.

IV. MEASURED I_c PROPERTIES

A. I_c Properties of Single and Stranded Nb_3Al Wires

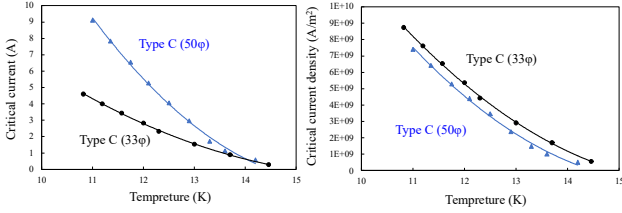


Fig. 6. The measured critical current and calculated critical current density of Type C wires with diameter of 33 μm and 50 μm .

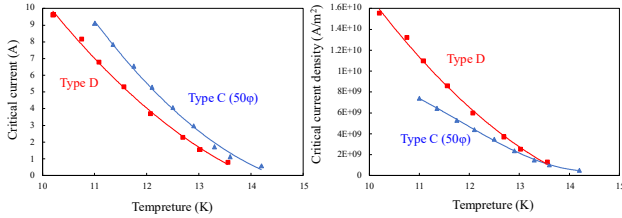


Fig. 7. The measured critical current and calculated critical current density of Type C and Type D wires with diameter of 50 μm .

Fig. 6 shows the measured critical current (I_c) and calculated critical current density (J_c) of single Nb_3Al wires (Type C) with diameter of 33 μm and 50 μm . I_c of 50 μm with a large superconducting area is higher than that of 33 μm diameter, but J_c is lower than that of a diameter of 33 μm . It is considered that the reaction distance between the Nb and Al foils was shortened by the wire drawing process, and the superconducting properties of Nb_3Al wires were improved. This result demonstrates the improvement of the critical current due to the ultrafine Nb_3Al wire. Fig. 7 shows the results of comparing the superconducting properties of two sample wires with the same wire diameter (50 μm) but different cross-sectional structures (Type C and Type D). The superconducting area of Type C is larger than that of Type D, and the I_c is also larger. However, the J_c of Type C is lower than that of Type D. This means that in the case of Type C, there is no barrier between the Cu outermost layer

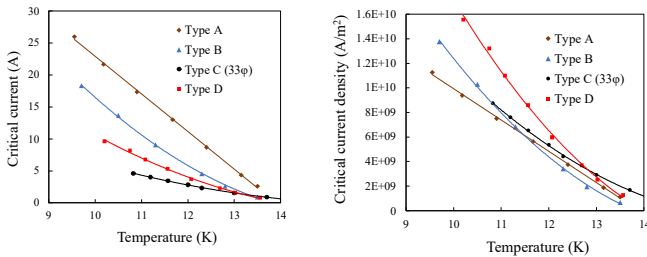


Fig. 8. The measured critical current and calculated critical current density of Type A, B, C (33 μm) and D wires to compare the effect of wire diameter.

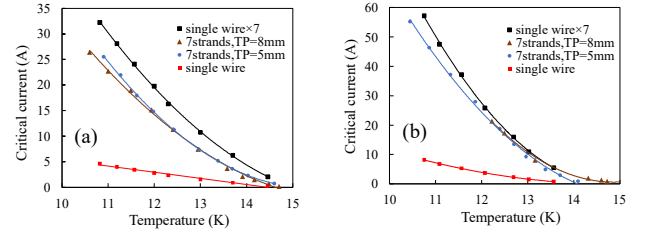


Fig. 9. The measured critical current of single and 7-stranded Nb_3Al wires with different twist pitch (a) Type C (33 μm) and (b) Type D.

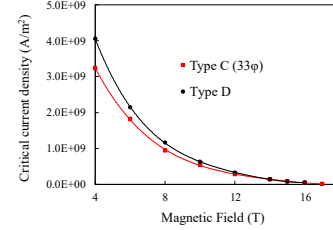


Fig. 10. The magnetic field dependence of the critical current density of Type C (33 μm) and Type D wires measured in liquid helium.

and Nb/Al, which may have reacted with Cu and reduced the superconducting properties. Therefore, this result shows the usefulness of the barrier and the copper core. A comparison of the I_c and J_c of the four sample wires (Type A, B, C and D) is shown in Fig. 8. The I_c increases in the order of increasing wire diameter, but the highest J_c was obtained with Type D.

Fig. 9 shows the measured critical current of single and 7-stranded Nb_3Al wires (Type C and Type D) with different twist pitch (5 and 8 mm). In these figures, the calculated the I_c of a single wire multiplied by 7 is also shown, and this value is larger than that of the 7-stranded wire. This is because the I_c of 7-stranded wire is larger than that of a single wire, and the magnitude of the self-field applied to itself is also larger. The difference between the I_c value of the 7-strand wire and that of the single wire multiplied by 7 is smaller for the Type D wire, and it is easy to predict that the J_c - B characteristic of Type D wire is higher than that of the Type C wire. In Fig. 9, no decrease in the critical current due to the twist pitch (5 and 8 mm) of the 7-strand wire was observed. Fig. 10 shows the magnetic field dependence of J_c for Type C and Type D wires measured in liquid helium. As expected, it was confirmed that the J_c - B characteristics of the Type D wire are better than that of Type C wire.

B. Bending Strain Characteristics

The bending radius characteristic of the critical current of a superconducting wire is a very important parameter in its application. Therefore, we measured the bending strain characteristics in the bending radius from 5 mm to 15 mm using Type



Fig. 11. Photographs of the pre-bended copper wire and sample stage to measure the bending strain characteristics of Type D wire.

D wire. Fig. 11 shows the photographs of the pre-bended copper wire and sample stage to measure the bending strain characteristics of Type D wire. In the experiment, the Nb_3Al wire was soldered along the inside of the pre-bent Cu wire as shown in Fig. 11. Fig. 12 shows the measured bending radius dependence of the I_c in Type D wire annealed at 850°C . When the bending radius is 15 mm (the bending strain ratio is 0.17%), the I_c decreased by 65% compared to the value of straight line. However, almost no decrease of I_c was observed in the range of bending strain ratio from 0.17% to 0.33%. The superconductivity of the Nb_3Al wire was destroyed when the bending strain ratio was less than 0.5% (the bending radius is 5 mm). The magnitude of the critical current of Type D wire annealed at 800°C was lower than that of the wire annealed at 850°C , but it was only 23% lower than that of the straight line when the bending radius was 15 mm. Therefore, we expect that the critical current and bending properties of Nb_3Al wires can be improved by optimizing the annealing process.

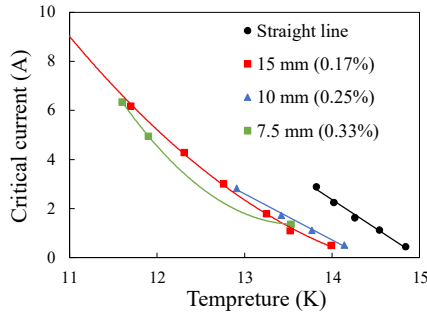


Fig. 12. The measured temperature dependence of the critical current of Type D wire with the straight line and bending radius of 7.5, 10 and 15 mm.

C. J_c Performance of the Developed Nb_3Al Wires

To demonstrate the performance of the developed Nb_3Al wire, a comparison of critical current densities of Nb_3Al , REBCO, NbTi and Nb_3Sn wires at 4.2 K and 0 T is shown in Fig. 13. The critical current density of the REBCO wire was taken from reference [6]. The thickness of the REBCO wire is $130\ \mu\text{m}$, the width is 4 mm and the thickness of the

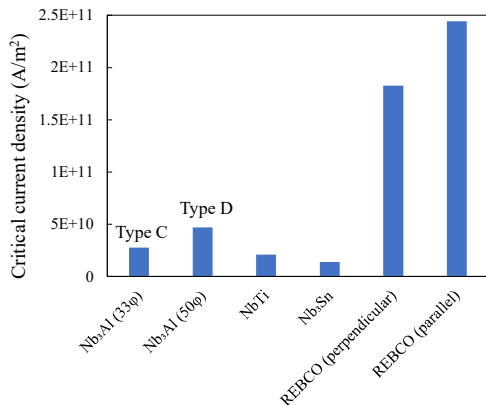


Fig. 13. The comparison of critical current density of Nb_3Al , REBCO, NbTi and Nb_3Sn wires at 4.2 K and 0 T.

superconducting layer is $1.9\ \mu\text{m}$. The critical current densities of NbTi and Nb_3Sn wires were taken from the reference [7] and [8] and fitted to the comparison conditions. The critical current densities of Nb_3Al wires at 0 T and 4.2 K are slightly higher than that of commercial NbTi and Nb_3Sn wires, but much lower than that of REBCO wires. As shown in Fig. 14, the critical current density in magnetic field of the developed ultrafine Nb_3Al wire is more than one order of magnitude lower than that of the REBCO wire. Therefore, further studies are needed to improve the critical current characteristics and flexibility of ultrafine Nb_3Al wires fabricated by the Jelly-rolled method.

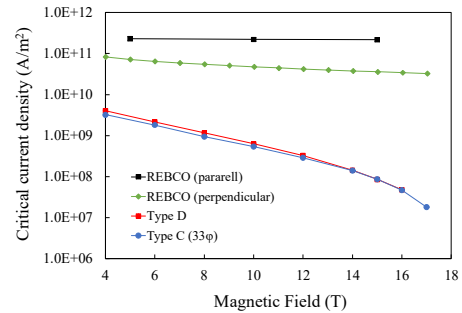


Fig. 14. The critical current densities in magnetic field of developed Nb_3Al wires and REBCO wire at 4.2 K.

V. CONCLUSION

In this study, the critical current properties of Nb_3Al wires with different cross-sectional structures fabricated by the Jelly-rolled method were investigated using a conduction cooling system. The current sweep and constant current methods were used to measure the critical current, and the current flowing in the copper wire soldered to the Nb_3Al wire to protect the sample wire was estimated to evaluate the correct critical current value. The Nb_3Al wire fabricated by the Jelly-rolled method showed improved critical current by reducing the wire diameter and the reaction distance between Nb and Al. The usefulness of the copper core used for the long length wire and flexibility of the Nb_3Al wire was confirmed. The critical current densities of Nb_3Al wires are slightly higher than that of commercial NbTi and Nb_3Sn wires, but much lower than that of REBCO wires. So, it is necessary to improve the J_c and J_c - B characteristics of Nb_3Al wires.

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