ASC2024-1MPo1C-06

Critical Current and AC Loss Characteristics of Ultrafine Nb₃Al and Nb₃Sn Superconducting Wires Under Conduction Cooling

SeokBeom Kim, Tomoya Sakamoto, Riku Onoue, Satoshi Nishikori, Ryota Inoue, Hiroshi Ueda, Akihiro Kikuchi, and Yasuo Iijima

Abstract— **Wind and React (W&R) technology is required to produce superconducting magnets using A15 superconducting wire. Recently, the Jelly-roll processed Nb₃Al and the bronze processed Nb₃Sn ultrafine superconducting wires with a wire diameter of less than 50 μm were fabricated by the National Institute for Materials Science (NIMS) in Japan. The ultrafine Nb₃Al and Nb₃Sn superconducting wires will enable the fabrication of superconducting magnets using the React and Wind (R&W) method. In order to apply Nb₃Al and Nb₃Sn ultrafine wires to DC and AC applications, it is necessary to clarify the temperature dependence of the critical properties and AC loss characteristics of these wires. In this study, the critical properties and AC transport loss characteristics of the developed Nb₃Al and Nb₃Sn ultrafine wires were experimentally determined using a cryocooler system. The critical temperature (T_c) and critical current density (J_c) of Nb₃Sn wire were higher than those of Nb₃Al wire, but the Nb₃Al wire showed a higher engineering critical current density (J_e) than the Nb₃Sn wire. The magnitude of AC transport current loss of the Nb₃Al wire was smaller than that of the Nb₃Sn wire with the same wire diameter.**

Index Terms—**ultrafine Nb₃Al & Nb₃Sn wires, critical properties, AC transport current losses, cryocooler system.**

I. INTRODUCTION

A15 superconducting wires such as Nb₃Sn and Nb₃Al are suitable for high magnetic field magnets, but their strain sensitivity requires the Wind & React (W&R) method. Therefore, there is a strong demand for the development of A15 superconducting wire that enables the fabrication of superconducting magnets by the React & Wind (R&W) method. The bending strain of A15 superconducting wire is expected to be minimized by reducing the wire diameter, and National Institute for Materials Science (NIMS) has been developing ultrafine A15 superconducting wire. Recently, the flexible ultrafine Nb₃Al mono-core (monofilament or mono-block) wires with a wire diameter of less than 50 μm were fabricated by the Jelly-roll process [1], [2]. In the Jelly-roll process, Ta, Nb, and Cu were tested as core materials to improve flexibility and drawability, and the amount relationship between the Cu core and the outermost layer of Cu stabilizer was investigated to increase the critical current density. The results of these studies, especially the critical current characteristics, have already been reported [3]. The bronze processed multifilamentary Nb₃Sn ultrafine superconducting wires were fabricated [4], and their J_c-B properties in liquid helium (bundle cable) and mechanical properties at room temperature (single wire) are measured and reported [5], [6].

The developed flexible Nb₃Al and Nb₃Sn wires are scheduled for application to DC (miniature high field coils) and AC (wireless power transmission) coils with cryogen-free conduction cooling, and the R&W method is expected to be applicable to these coil fabrications. To achieve this research goal, it is necessary to evaluate the temperature dependence of the critical and AC loss properties of the developed ultrafine wires. In this study, the both properties of Nb₃Sn and Nb₃Al single wires with different wire diameters were experimentally evaluated using a conduction cooling system.

II. NB₃AL AND NB₃SN ULTRAFINE WIRES

Fig. 1 shows the cross-sectional view of Nb₃Al and Nb₃Sn wires with wire diameter of 50 μm, and specifications of both wires are listed in Table I. Two samples of Nb₃Al wire were prepared with wire diameters of 33 μm and 50 μm, and the area ratio of the Cu core to the outermost Cu layer is 1:1. The Nb₃Sn wires have diameters of 30 μm and 50 μm and consist of 19 filaments. The diameter of the filament in the Nb₃Sn wire with
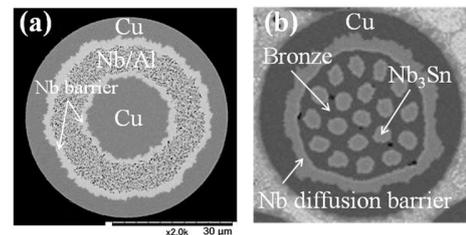

Fig. 1. Cross-sectional view of the (a) Jelly-roll processed mono-block Nb₃Al wire and (b) Bronze processed the 19-filaments Nb₃Sn wire.

TABLE I
SPECIFICATIONS OF NB₃AL AND NB₃SN WIRES

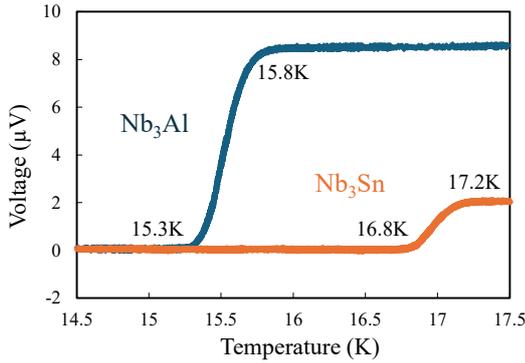|	Nb₃Al wire		Nb₃Sn wire	
Process	Jelly-roll method		Bronze method	
Wire diameter (μm)	33	50	30	50
Cu/Non-Cu ratio	1.0		0.89	
Barrier material	Nb		Nb	
Superconducting area (×10⁻¹⁰ m²)	2.8	6.5	0.48	1.34
Superconducting portion (%)	33		6.8	

Fig. 2. Measured the critical temperature of Nb₃Al and Nb₃Sn wires by 4-probe method with 1 mA in cryocooler system.

a wire diameter of 50 μm is 3 μm. The superconducting region of the Nb₃Al wire has a cylindrical structure, while the Nb₃Sn wire has a filament structure. The area of the superconducting region of the Nb₃Al wire is larger than that of Nb₃Sn wire, and the proportion of the superconducting region of the Nb₃Al wire is 33% (Nb₃Sn wire is 6.8%).

Fig. 2 shows the critical temperatures (T_c) of both wires measured by the DC four probe method with 1 mA in the cryocooler system. The T_c of the Nb₃Al wire is approximately 15.5 K and ΔT is 0.5 K, and Nb₃Sn wire is approximately 17 K and ΔT is 0.4 K. The T_c of the Nb₃Sn wire shows almost the same value measured by the magnetic moment method with 1 mT [5].

III. CRITICAL CURRENT PROPERTIES

The sample wire placed on the sample stage in the cryocooler system is adiabatic state except for the current leads. Therefore, wire breakage can easily occur when measuring the critical current of ultrafine wires. In a previous study, a sample wire was soldered to a copper wire to prevent wire breakage during critical current measurement [3]. However, in this study, since the critical current and AC transport loss of ultrafine wires are measured at the same time, a copper wire cannot be attached. So, in this study, the critical current of ultrafine wires was measured by carefully combining the pulse current and current sweep methods. Although we measured while being careful, many of the sample wires broke, especially those with diameters of 33 μm or less. Since it is very difficult to directly measure the temperature of the ultrafine wires, the temperatures
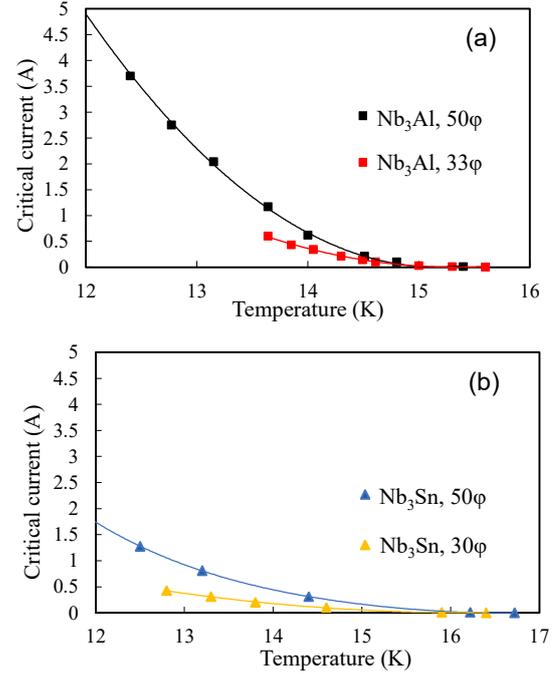

Fig. 3. Temperature dependence of the measured critical current of (a) Nb₃Al and (b) Nb₃Sn wires in self-magnetic field.
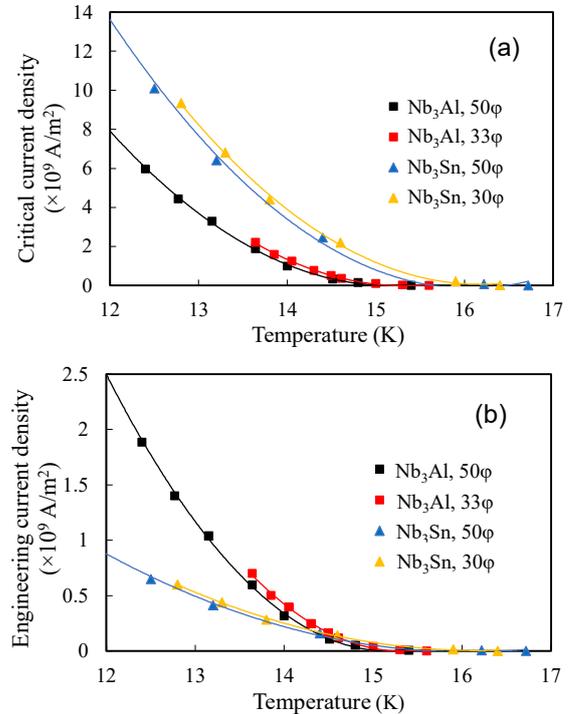

Fig. 4. (a) Critical current density of Nb₃Al and Nb3Sn wires calculated by area of superconducting region and (b) engineering current density calculated by total cross-sectional area of wire.

of the aluminum nitride sample stage and the copper current leads were used as the reference temperatures. Details of the measurement system using a conduction cooling system are described in previous studies [3], [7].

Fig. 3 shows the measured the critical current (I_c) of four sample wires, and critical current density (J_c) and engineering current density (J_e) are shown in Fig. 4. The J_c of the sample wires are calculated by dividing the I_c value by the area of the superconducting portion, so it is different from the Non-Cu J_c. The value of J_e is the I_c value divided by the total cross-sectional area of the wire. The J_c of the Nb$_3$Sn wire at 12 K is almost the same with the value of the REBCO wire at 77 K (3×10^{10} A/m^2). It is clear that the I_c of Nb$_3$Al wire is higher than that of Nb$_3$Sn wire, but the J_c of Nb$_3$Sn wire is higher than that of Nb$_3$Al wire. From the measured T_c and J_c values, we can say that the superconducting properties of the Nb$_3$Sn wire are better than Nb$_3$Al wire, but Nb$_3$Al wire has an advantage in terms of J_e. The temperature dependence of the n-values of the sample wires were obtained from the I-V curves during I_c measurement by current sweep and pulse current methods. The n-values of the four sample wires from 8 K to 15 K are 2 to 8. These values are very small and affect the AC transport current loss characteristics. Incidentally, the n-values of 19-strands Nb$_3$Sn wire in liquid helium are 13 to 80 (@1-18T) [5].

IV. AC Transport Current Loss Characteristics

Several institutions have tried to measure the AC transport current losses of the developed Nb$_3$Al and Nb$_3$Sn ultrafine wires in a conduction-cooled system. However, no one has measured it yet, because heat generation in the wire under adiabatic conditions is the cause. After measuring I_c of the sample wires by the 4-probe method, the AC transport current losses were measured. The AC transport current losses in the ultrafine sample wires were measured by the standard technique (electrical method) with a lock-in amplifier [8]. The output AC current from the power supply and reference signal for the lock-in amplifier were controlled and applied by multifunction generator. The phase of the reference was adjusted using a Rogowski coil.

Figs. 5 and 6 show the frequency dependence of AC transport current losses of Nb$_3$Al and Nb$_3$Sn wires as a function of amplitude of AC current. In Fig. 5, the AC transport current losses slightly increase with the frequency at large current values, and this might be due to the temperature increasing in the wire. However, the measured frequency and current dependence of the AC losses indicates hysteresis loss due to the superconductivity of the sample wires. Although the AC transport current losses were small because the magnitude of the applied current was small, it is clear that the AC losses could be measured under conductive cooling from the results in Figs. 5 and 6.

Figs. 7 and 8 show the dependence of AC transport current losses on wire diameter in Nb$_3$Al and Nb$_3$Sn wires at 400 Hz. The peak value of applied AC current (I_p) is normalized with the I_c of the wire at each temperature. The AC losses were

divided by the square of I_c to allow comparisons between wires with different critical currents. In Figs. 7 and 8, the dash-dotted line represent theoretical value in the round wire based on the Bean model [9], [10]. In the region of low values of I_p/I_c, the experimental values are larger than the theoretical values, and in the region of high values of I_p/I_c, the experimental values are smaller than the theoretical values. Such results are rarely observed, the discrepancy between the measured values and the
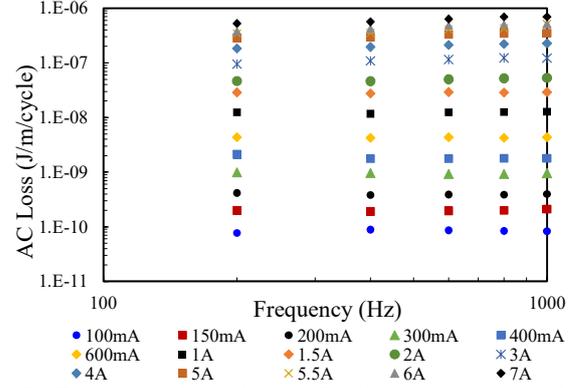

Fig. 5. Frequency dependence of AC transport current losses of Nb$_3$Al wire with wire diameter of 50 μm as a function of amplitude of AC current at 7.3 K.
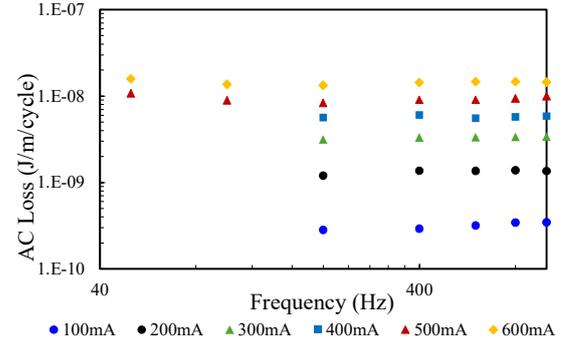

Fig. 6. Frequency dependence of AC transport current losses of Nb$_3$Sn wire with wire diameter of 30 μm as a function of amplitude of AC current at 7 K.
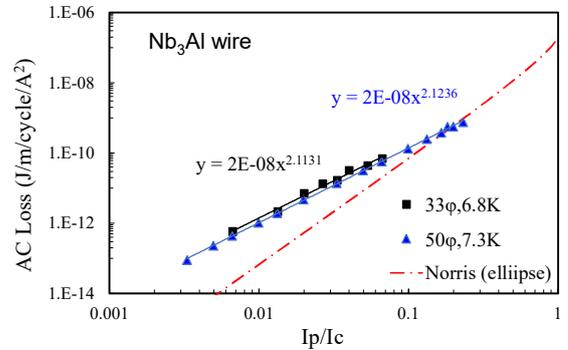

Fig. 7. Dependence of AC transport current losses on wire diameter in Nb$_3$Al wire at 400 Hz. The dash-dotted line represent theoretical value in the round wire based on the Bean model.
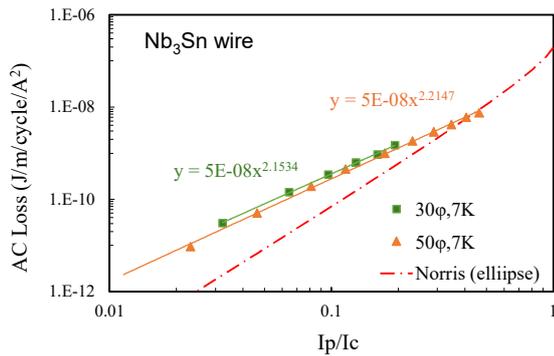
ASC2024-1MPo1C-06

Fig. 8. Dependence of AC transport current losses on wire diameter in Nb$_3$Sn wire at 400 Hz. The dash-dotted line represent theoretical value in the round wire based on the Bean model.
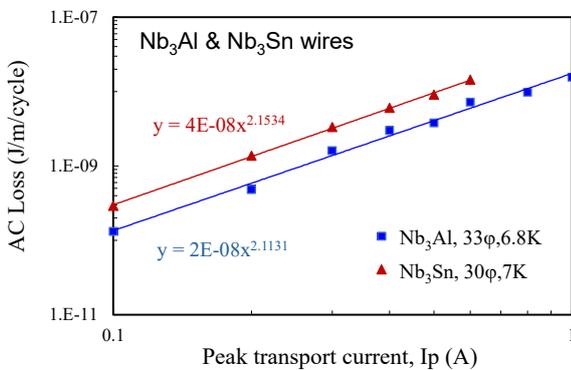

Fig. 9. Comparison of AC transport current losses between Nb$_3$Al and Nb$_3$Sn wires with the same wire diameter (30 and 33 μm).
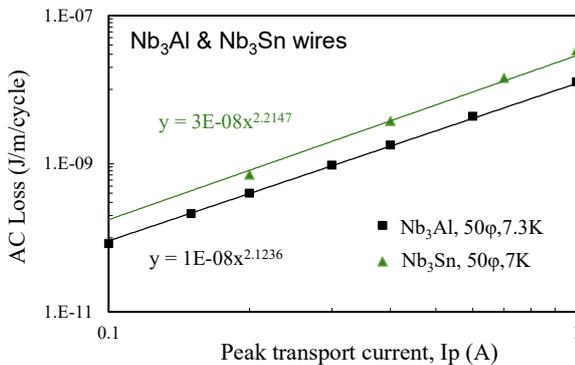

Fig. 10. Comparison of AC transport current losses between Nb$_3$Al and Nb$_3$Sn wires with the same wire diameter (50 μm).

theoretical values based on the Bean model might be due to the low *n* value of the sample wire. It may be unreasonable to apply the Bean model to superconductors with small *n* value. However, the dependence of AC transport current losses on wire diameter was not observed. Figs 9 and 10 show the compare the AC losses of Nb$_3$Al and Nb$_3$Sn wires at approximately the same wire diameter and approximately the same temperature. The AC transport current losses of Nb$_3$Sn wires with filamentary structure are larger than that of Nb$_3$Al

wires with cylindrical structure (mono-block) when the wire diameter, I_p and I_p/I_c are the same. The filaments in the Nb$_3$Sn wire are arranged along concentric circles, and the inductance of the outer filaments is lower than that of the inner filaments. Therefore, it is expected that the current is biased to the outermost filaments, the I_p/I_c value of the outermost layer increases, and the AC transport loss increases.

V. CONCLUSION

Even though many sample wires were broken during the experiment due to mechanical and thermal reasons, the I_c and AC loss properties of the developed ultrafine Nb$_3$Al and Nb$_3$Sn wires were successfully measured under conduction cooling. The superconducting properties (T_c and J_c) of Nb$_3$Sn wire are better than that of Nb$_3$Al wire, but Nb$_3$Al wire has an advantage in terms of engineering current density (J_e). The magnitude of AC transport current loss of the mono-cored Nb$_3$Al wire is smaller than that of the 19-filaments Nb$_3$Sn wire.

REFERENCES

[1] A. Kikuchi, *et. al.*, "Trial manufacturing of Jelly-Rolled Nb/Al monofilamentary wire with very small diameter below 50 microns," *IOP Conf. Ser., Mater. Sci. Eng.* 756 art no. 012016, 2020.

[2] A. Kikuchi, *et. al.*, "Ultra-fine Nb3Al mono-core wires and cables," *IEEE Trans. Appl. Supercond.*, vol. 31, no. 5, 6000105, Aug. 2021.

[3] H. Fukuda, *et. al.*, "Experimental study on the critical current properties of flexible Nb3Al superconducting wires in cryocooler system," *IEEE Trans. Appl. Supercond.*, vol. 33, no. 5, 6000704, Aug. 2023.

[4] A. Kikuchi, *et. al.*, "The bronze processed Nb3Sn ultra-thin superconducting wires," *IEEE Trans. Appl. Supercond.*, vol. 32, no. 4, 6000104, Jun. 2022.

[5] X. Wang, *et. al.*, "Superconducting properties of a Nb3Sn bundle cable made of ultra-fine wires," *IEEE Trans. Appl. Supercond.*, vol. 33, no. 5, 6000105, Aug. 2023.

[6] M. Sugano, *et. al.*, "Mechanical properties of ultra-thin Nb3Sn composite wires," *IEEE Trans. Appl. Supercond.*, vol. 33, no. 5, 8400905, Jun. 2023.

[7] S.B. Kim *et al.*, "Critical characteristics of ultrafine Nb3Al superconducting wires under conduction cooling conditions." *IEEE Trans. Appl. Supercond.*, vol. 32, no. 6, 6001005, 2022.

[8] K. Kajikawa, *et. al.*, "Dependence of transport-current losses in MgB2 superconducting wire on temperature and frequency," *IEEE Trans. Appl. Supercond.*, vol. 20, no. 3, pp.2111-2114, 2010.

[9] C. P. Bean, "Magnetization of hard superconductors," *Phys. Rev. Lett.*, vol. 8, no.6, pp.250-253, 1962.

[10] H. London, "Alternating current losses in superconductors of the second kind," *Phys. Lett.*, vol. 6, no. 2, pp.162-165, 1963.