Development of Nb_3Al Wires for Future Accelerator Magnets and Measurements of their Critical Current Density and Critical Temperature

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Abstract

Recent studies in RHQ processed Nb_3Al wires for future accelerator magnets are presented and discussed. The test wires were prepared with different fabrication parameters, such as Nb matrix ratio, RHQ current, area reduction ratio of the wire after RHQ treatment and heat treatment condition, and the measurements of critical current density (J_c) and n-value have been performed during past several years. Recently, we performed the critical temperature (T_c) measurement and the relationship between J_c and T_c were investigated from Nb matrix and area reduction effect. Currently achieved highest non-copper J_c is 2171 A/mm^2 at 10 T with 29 % area reduction.

INTRODUCTION

The LHC as a largest superconducting accelerator project is now under construction to be completed by 2007 [1]. The R&D for the luminosity upgrade as a next project has already been started in the world [2]. To aim at the luminosity upgrade, the large aperture, high field and large field gradient are required for dipole and quadrupole magnets installed in LHC collision points. These requirements are beyond the technology of present NbTi superconducting accelerator magnets. In EU [3] and USA [4], the Nb_3Sn wire is currently developed as a candidate of new high field superconducting wire from points of view of superconducting properties in high field, availability and cost. In Japan, we are presently developing the Nb_3Al wire produced by rapid heating and quenching (RHQ) process [5]. It had been developed by National Institute for Materials Science (NIMS). The mechanical strain tolerance of Nb_3Al wire is larger than that of Nb_3Sn wire. Thus, Nb_3Al wire can be applied to future high field accelerator magnet than Nb_3Sn wire. But, current J_c of Nb_3Al is smaller than that of Nb_3Sn. So, we have been developing Nb_3Al wire since 2001 to increase the non-copper critical current density (J_c) under high field (10∼17T). In this paper, adding to J_c properties [6], we want to summarize their critical temperatures.

EXPERIMENT

Wire production and sample parameter

The starting monofilament is assembled by rolling Nb and Al foils around a pure Nb core, and then extruded and drawn to a wire. The Nb/Al atomic ratio in the filaments is designed as 1/3, which is the stoichiometric A15 composition. The monofilament wires are re-stacked into the multifilament billet and the billet is drawn to a wire of final size. In the RHQ operation, these precursor wires were rapidly heated up to about 2000 °C for about 200 ms by ohmic heating of a constant current (I_{RHQ}) passing through a section of the wire, which is moving at a constant velocity, between a Cu electrode pulley and molten Ga bath at about 40°C. Through this process, the Nb/Al composite filaments are converted into the Nb/Al supersaturated bcc solid solution $(NbAl)_{ss}$). For the RHQ processed Nb_3Al wires, the RHQ condition is an essential processing parameter, then determines the critical characteristics of the Nb_3Al. The stabilizing copper of 170 μm is electrically plated on the surface of the wires. Then, a heat treatment of 600 °C × 1 hour is given to stabilize the bonding between copper and Nb. The typical volume ratio of Cu/non-copper is about 1.0 and the RRR is about 150. Figure 1 shows a typical wire cross section of a sample with Cu stabilizer. The specification of the prepared samples for this study are listed in the table 1. They have different Nb matrix ratio (Nb matrix volume/filaments volume) to search Nb matrix effect. To find optimized I_{RHQ} on J_c, we made three kinds of wires by three I_{RHQ} currents for each sample.

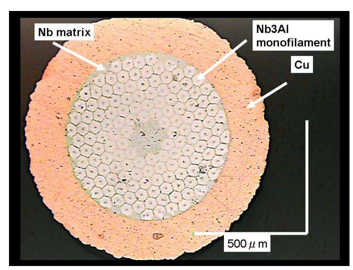

Figure 1: The wire cross section of M21-4 sample with Cu stabilizer.

Sample preparation and experimental methods

After copper electro-plating, we applied area reduction (AR) process up to 60 % to reduce cross section by dice drawing. Each wire is wound on a cylindrical heat-treatment former, which is made of stainless steel. The size of the cylinder is about 48 mm in diameter, which diameter fit to the G-10 holder for I_c measurements. These wires were heated in a vacuum furnace for the phase transformation in about 10^{-6} mbar. The temperature ramp up rate was typically 800 °C per an hour, then kept 800 °C for

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Table 1: The specification list of prepared samples.

Sample name	M21-1	M21-2	M21-3	M21-4	M21-5	ME396	ME451
Wire dia. (mm)	0.8						1.35
Nb Matrix ratio	1.0	1.0	0.8	0.6	0.8	0.6	0.7
# of filaments	144					304	294
Fila. dia. (μm)	48.2		51.0	54.0	51.2	38.0	62.7
Fila. spa. (μm)	7.6	4.6			3.0	3.0	6.4

10 hours. For critical current (I_c) measurements, after the heat treatment, the wire was carefully moved from stainless steel bobbin to cylindrical G-10 holder which can accommodate four wires. The wire length is 340 mm. Two voltage taps were soldered over the central 150 mm of the wire. The critical current is defined at a voltage of 3 μV (this corresponds to a sensitivity of 20 μV/m). Magnetic field was given to wires from 7 T to 17 T to study the dependence of J_c on magnetic field. The current was supplied in such a way that the Lorentz force was acting inwards to press against the sample holder. The n-value was determined in the 10 μV/m to 40 μV/m range by fitting the V-I curve with the function of $V \sim I^n$. For T_c measurements, the short sample (about 40 mm) was cut from the sample used in I_c measurements. We measured the T_c by four-terminal methods. The sample was attached to G-10 plate holder which can accommodate six samples. Two voltage taps were soldered over the central about 10 mm of the sample. The temperature was decreased from 20 K to 11 K at a sweep rate of 0.1 K/min. The external magnetic field was given by split magnet from 0.5 T to 12 T to see the dependence of T_c on magnetic filed. The magnetic field was given in such a way that the magnetic field is perpendicular to the current direction. In this study, T_c was defined to be the temperature indicated by 50% level of the voltage between normal state and superconducting state. Supplied current was 0.1 A.

THE RESULTS AND DISCUSSION

The dependence of J_c and T_c on Nb matrix ratio

Figure 2 shows the Nb matrix effect on J_c at 15 T. When seeing a sample which has a highest J_c in same Nb matrix sample, from Nb matrix ratio of 1.0 (M21-1) to 0.7 (ME451), J_c increases by a factor of 1.21. The highest J_c of 689 A/mm^2 is achieved in ME451 which has Nb matrix ratio of 0.7. The increasing ratio of J_c is slightly larger than the expected increasing ratio (1.18) estimated from superconducting volume ratio between 1.0 (M21-1) and 0.7(ME451). However, T_c is independent of Nb matrix ratio in figure 3 within systematic error. The difference between M21-1 and M21-4 is 0.01 K at 0 T. The systematic errors on T_c are 0.01 K at 0 T and 1 % at 10 T. However, when we reduce Nb matrix ratio from 0.7 (M21-3) to 0.6 (M21-4), J_c decrease 94 % against our expectation. In ME396 sample intended to increase J_c with Nb matrix ratio, J_c decreases by 56 % comparing with M21-4. The J_c of M21-2 is smaller than M21-1 by 61 %. So, we searched the correlation between J_c and n-value on Nb matrix ratio to find the reason.

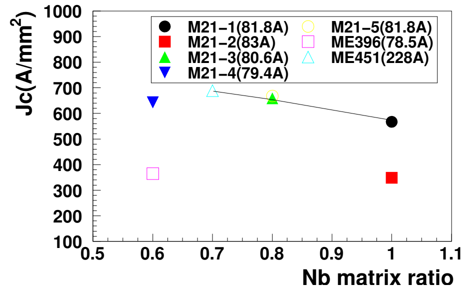

Figure 2: Nb matrix ratio effect on J_c at 15 T. Each symbols show prepared samples treated by optimized I_{RHQ} current. Optimized I_{RHQ} current is written in parentheses.

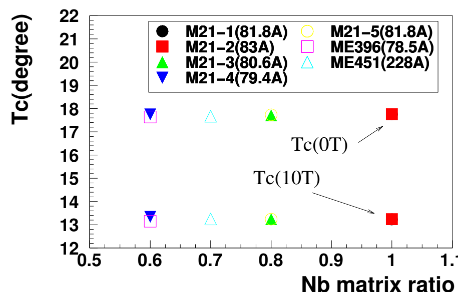

Figure 3: Nb matrix ratio effect on T_c at 10 T and 0 T.

Figure 4 shows the correlation between J_c and n-value at 15 T. There are clear correlations J_c and n-value. In the case of same Nb matrix ratio, for example, M21-1 and M21-2, or, M21-4 and ME396, low J_c has low n-value in spite of same Nb matrix ratio. The J_c of M21-1 is lowest in our prepared samples and n-value is also lowest. However, T_c is almost same in all samples, Thus, because there are differences about filament diameter and filament space, we suppose from view points of n-value and T_c behaviors that the structure of wire cross section has an effect on superconducting characteristics, then makes J_c lower. Therefore, it is very important to optimize the structure parameter of wire cross section to increase J_c.

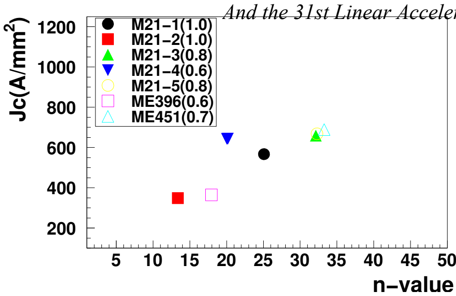

Figure 4: Correlation between J_c and n-value for Nb matrix ratio at 15 T. The Nb matrix ratio is written in parentheses with I_{RHQ} current.

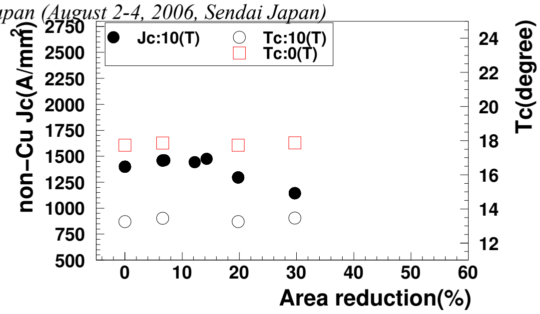

Figure 6: The J_c and T_c is plotted as a function of area reduction (%) in M21-3 (79.4A).

Area reduction effect on J_c and T_c

The figure 5 shows the area reduction effect on J_c and T_c in M21-3 (80.6 A). The different symbol in the figure shows the results under different magnetic field. In this sample, the J_c increases with AR from 0 % to 29 % by about 36 % (from 0% to 41 %, about 28 % up) at 10 T. This sample (AR=29 %) has highest J_c of 2171 A/mm^2 at 10 T in our study. In case of T_c, the increasing ratio by AR from 0 % to 56 % is about 1.4±1.0 % (0.18 K) at 10 T. In 0 T, increasing ratio of T_c is about 0.1±0.001 % (0.16 K) almost same as 10 T. The T_c is independent of the area reduction process considering systematic error.

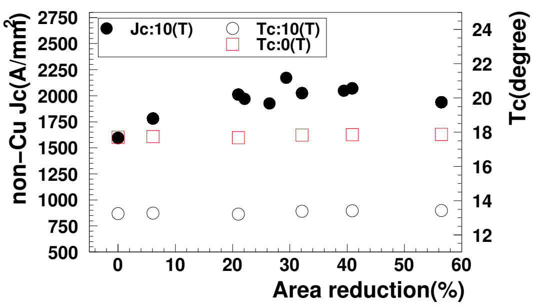

Figure 5: The J_c and T_c is plotted as a function of area reduction (%). Each color show the results of different magnetic field in M21-3 (80.6 A) samples

In figure 6, the J_c and T_c as a function of AR for another wire sample is plotted. They have different behavior from M21-3 (80.6A). J_c decreases with more than 10∼20 % AR in M21-3 (79.4A). However, the T_c is same as M21-3 (80.6) (17.71 K (80.6 A) and 17.73 K (79.4 A) at 0 T) and independent of AR. The difference of their behaviors is caused by difference of I_{RHQ} current between 79.4 A and 80.6 A. We suppose that the superconducting quality in I_{RHQ} current is different between 79.4 A and 80.6 A. Thus, in this study, it is found that J_c increases by AR process and it is very important to control I_{RHQ} current in narrow current region (1.2 A in M21-3 sample).

Figure 7 shows the dependence J_c and T_c on magnetic field in M21-3 (80.6A) sample which shows the highest performance. The T_c shows a almost linearity to magnetic field against J_c. T_c is 13.24 K and 17.71 K at 10 T and 0 T respectively. In J_c, from 17 T to 10 T, the dJ_c/dB (=211) by AR=29 % is slightly larger than that (=171) by AR=0 %. In this figure, the J_c is 1655 A/mm^2 at 12 T. We aim at increasing the J_c up to 2500 A/mm^2 at 12 T to apply the LHC upgrade magnet because J_c of Nb_3Sn is about 2750 A/mm^2 at 12 T.

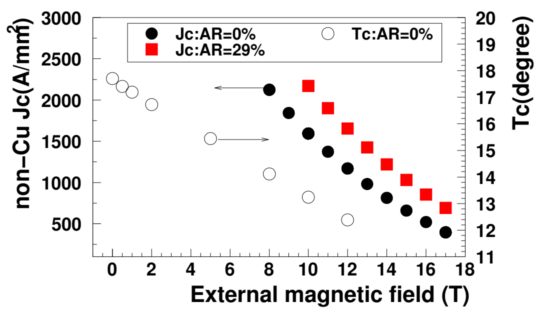

Figure 7: A typica the dependence of J_c and T_c on magnetic field in M21-3 with I_{RHQ} of 80.6 A.

SUMMARY

There is the dependence of J_c on Nb matrix ratio from 1.0 to 0.7. ME451 of Nb matrix ratio of 0.7 has highest J_c of 689 A/mm^2 at 15 T without AR. T_c is independent of Nb matrix ratio against J_c. But, J_c and n-value have strong correlation. It is supposed that lower J_c is caused by the different structure of wire cross section from points of view of T_c and n-value behaviors on Nb matrix ratio. For AR effect, the J_c of M21-3 samples have a dependence on AR clearly. The M21-3 (80.6A) sample has sample record of 2171 A/mm^2 at 10 T with 29 % AR. The J_c increases by 36 %. On the other hand, T_c is independent of AR within 1.9%. Now, we are developing the wire of Nb matrix ratio of 0.6 and 0.7 in order to increase J_c. In this development, we think that we need to control I_{RHQ} and to optimize structure parameters of wire cross section based on this study.

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