Development of Nb₃Al 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 Nb₃Al 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 (Jc) and n-value have been performed during past several years. Recently, we performed the critical temperature (Tc) measurement and the relationship between Jc and Tc were investigated from Nb matrix and area reduction effect. Currently achieved highest non-copper Jc is 2171 A/mm² 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 Nb₃Sn 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 Nb₃Al 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 Nb₃Al wire is larger than that of Nb₃Sn wire. Thus, Nb₃Al wire can be applied to future high field accelerator magnet than Nb₃Sn wire. But, current Jc of Nb₃Al is smaller than that of Nb₃Sn. So, we have been developing Nb₃Al wire since 2001 to increase the non-copper critical current density (Jc) under high field (10~17T). In this paper, adding to Jc 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 Al5 composition. The monofilament wires are re-stacked into the multi-filament 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 (IRHQ) 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)₃. For the RHQ processed Nb₃Al wires, the RHQ condition is an essential processing parameter, then determines the critical characteristics of the Nb₃Al. 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 IRHQ on Jc, we made three kinds of wires by three IRHQ 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 Jc 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
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 $\mu$V (this corresponds to a sensitivity of 20 $\mu$V/m). Magnetic field was given to wires from 7 T to 17 T to study the dependence of $I_c$ 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 $\mu$V/m to 40 $\mu$V/m range by fitting the V-I curve with the function of V$^{-n}$ for $T_c$. 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/mm² 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.](image1)

![Figure 3: Nb matrix ratio effect on $T_c$ at 10 T and 0 T.](image2)

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 $J_c$. 

### Table 1: The specification list of prepared samples.

<table>
<thead>
<tr>
<th>Sample name</th>
<th>M21-1</th>
<th>M21-2</th>
<th>M21-3</th>
<th>M21-4</th>
<th>M21-5</th>
<th>ME396</th>
<th>ME451</th>
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<tr>
<td>Wire dia. (mm)</td>
<td>0.8</td>
<td>1.35</td>
<td>1.35</td>
<td>1.35</td>
<td>1.35</td>
<td>1.35</td>
<td>1.35</td>
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<td>Nb Matrix ratio</td>
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<td>1.0</td>
<td>0.8</td>
<td>0.6</td>
<td>0.8</td>
<td>0.6</td>
<td>0.7</td>
</tr>
<tr>
<td># of filaments</td>
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<td>304</td>
<td>294</td>
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<td>294</td>
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<tr>
<td>Filia. dia. (±µm)</td>
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<td>51.0</td>
<td>54.0</td>
<td>51.2</td>
<td>38.0</td>
<td>62.7</td>
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<td>Filia. spa. (±µm)</td>
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<td>4.6</td>
<td>3.0</td>
<td>3.0</td>
<td>6.4</td>
<td>6.4</td>
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</tr>
</tbody>
</table>

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**Table 1: The specification list of prepared samples.**

The variable names M21-3, M21-4, and ME451 are used to represent wire samples with different Nb matrix ratios. The Nb matrix ratio is a key parameter that affects the critical current ($J_c$) and transition temperature ($T_c$) of these superconducting wires. The table provides a detailed list of the wire samples, including their wire diameters, Nb matrix ratios, and the number of filaments. The data show that as the Nb matrix ratio decreases, the critical current increases, indicating a positive correlation between the two variables. However, the transition temperature does not exhibit a similar trend, suggesting that other factors might be influencing this parameter.
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\times10^{-2}$ from 0 % to 1.4. In 0 T, increasing ratio of $T_c$ is about 0.1 to 0.01 % (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 $T_c$ are 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 to 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 $I_{RHQ}$ 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$_3$Sn is about 2750 A/mm$^2$ at 12 T.

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

Figure 7: A typical 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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REFERENCES


