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| 著者 | 津田　理 |
| journal or publication title | IEEE Transactions on Applied Superconductivity |
| volume | 12 |
| number | 1 |
| page range | 1033-1036 |
| year | 2002 |
| URL | http://hdl.handle.net/10097/46516 |

doi: 10.1109/TASC.2002.1018577

# Influence of Rapid Heating Condition on Superconducting Properties in Transformed Jelly-Roll $Nb_3Al$ Multifilamentary Wire

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***Abstract*—Understanding the variation of the superconducting properties as a function of the maximum heat treatment temperature or heating time in jelly-roll $Nb_3Al$ wire is important for the optimization of the rapid heating conditions. Jelly-roll $Nb_3Al$ wires with a Nb matrix were ohmically-heated to maximum temperatures ranging from 1900 to 2300 °C in vacuum in order to optimize the rapid heating conditions and to investigate the superconducting properties for this transformation method. The diameter of the wire was 0.94 mm. The sample was monitored using a noncontact measurement technique employing a photodiode to measure high temperatures (over 2000 °C) during rapid heating. After the surface temperature reached a maximum, the sample was quenched in liquid gallium. The samples were annealed for 10 hours at 800 °C after the rapid heating process to transform the bcc-phase to the A15 phase. The superconducting properties including DC magnetization and critical current were explored for various maximum heating temperatures and heating times. The magnetic field dependence of the pinning force density was investigated for these various conditions.**

***Index Terms*—$Nb_3Al$, ohmic heating, pinning force density, superconducting materials.**

## I. INTRODUCTION

$Nb_3Al$ has a high upper critical field (over 25 T) at 4.2 K and a relatively small critical-current degradation with increasing mechanical strain as compared to $Nb_3Sn$. New $Nb_3Al$ multifilamentary wires have been developed for 1 GHz NMR magnets in Japan. The superconducting properties of $Nb_3Al$ are sensitive to compositional variation. To form the stoichiometric composition in the A15-phase, a rapid quench from the stable region at high temperatures is needed. High critical current densities at high magnetic fields have been obtained by the fabrication of fine $Nb_3Al$ grains transformed from supersaturated bcc-solid-solution Nb(Al)ss [1], [2]. The rapid ohmic-heating and quenching method has been developed to realize this technique for jelly-roll multifilamentary wire.

Manuscript received September 24, 2001.

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Publisher Item Identifier S 1051-8223(02)03882-4.

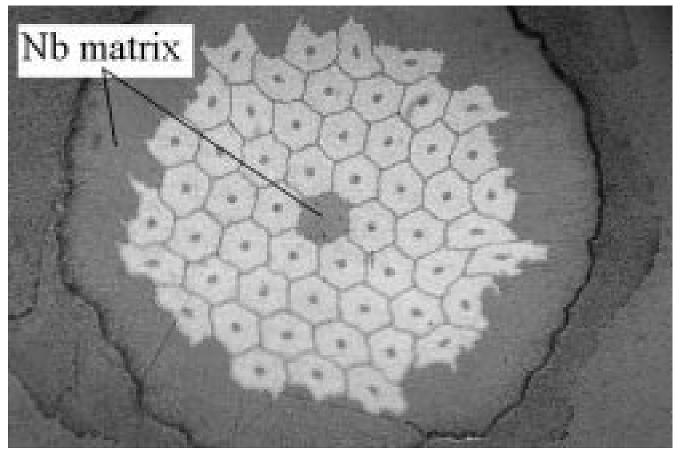


Fig. 1. Cross sectional micrograph of jelly-roll $Nb_3Al$ multifilamentary wire with Nb matrix.

Influences of rapid heating conditions on superconducting properties have been investigated by using a noncontact measurement technique employing a photodiode to measure high temperature (over 2000 °C) during rapid heating [3]–[6]. Also the supersaturated bcc-solid-solution Nb(Al)ss after quenching is considered to be due to the phase change at a temperature over the melting point of $Nb_3Al$ (1940 °C) [5]. An optimization of this rapid heating condition is important in order to improve the properties of critical current density in high magnetic fields.

This paper describes the superconducting properties observed during an optimization study of rapid heating processing of jelly-roll $Nb_3Al$ multifilamentary wires. Short samples with various maximum temperatures and times have been prepared. Superconducting properties including DC magnetization and critical current after rapid heating have been explored for various maximum heating temperatures and times. Moreover, the magnetic field dependence of pinning force density is investigated in order to improve the properties at high magnetic fields.

## II. EXPERIMENTS

### A. Rapid Heating and Quenching System

A cross-sectional micrograph of a Jelly-roll $Nb_3Al$ multifilamentary wire used in this study is shown in Fig. 1. This wire (YI) [5] is 0.94 mm in diameter and is composed of 54 filaments and a Nb matrix. Equipment with an autotransformer, a transformer and a temperature measurement system [5] was used to

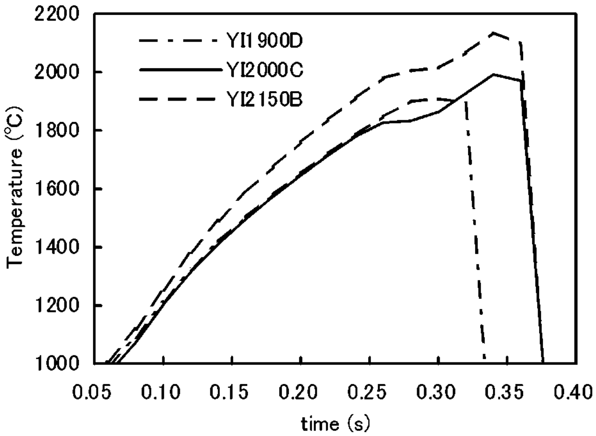


Fig. 2. Temperature at the sample surface during rapid heating.

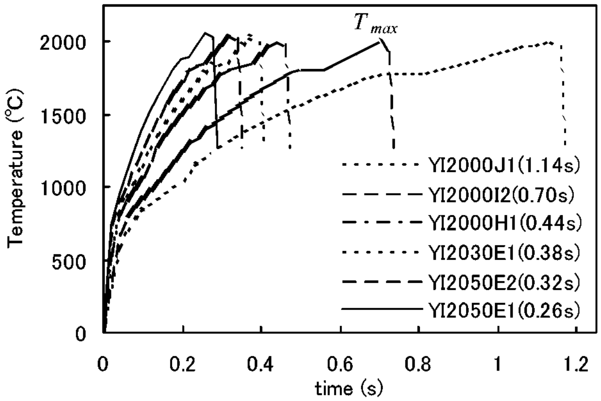


Fig. 3. Temperature at the sample surface during rapid heating.

perform rapid heating and quenching of the strand samples. In this method a current flows through a sample of 70 mm length placed in the vertical direction. The top was held in a movable electrode and the end part was soaked in a liquid gallium bath. AC current flows between the movable electrode and the liquid gallium bath. As soon as the temperature of the sample reaches the maximum temperature $T_{\max}$, the sample is quenched into the liquid gallium. Two kinds of samples were prepared, one set with various $T_{\max}$ and one set with various heating times. In the set with various $T_{\max}$ the heating time was fixed at about 0.3 to 0.4 sec. In the set with various heating times $T_{\max}$ was fixed to be 2000 °C to 2050 °C. The heating time were determined by the voltage applied to the sample. The surface temperature in the center part of the sample was measured by a photodiode. The temperature was calibrated using an optical pyrometer and was measured from the voltage generated by the photodiode. The rapid heating samples were annealed for 10 hours at 800 °C [5] in an argon atmosphere to transform the $Nb_3Al$ and to order the A15-phase.

### B. Measurements of Superconducting Properties

Critical currents in magnetic fields up to 23 T at 4.2 K in liquid helium were measured in the hybrid magnet, HM-2, at the High Field Laboratory for Superconducting Materials in Tohoku University. The magnetic field was applied perpendicularly to the longitudinal direction of the copper plated sample. The samples of about 30 mm long were measured by a four-probe method, with the voltage taps separated by 5 mm. The critical current criterion was $10 \times 10^{-6}$ V/cm. The critical current density was defined as the critical current divided by the area of jelly-roll region in the precursor wire. The pinning force density, $Fp$, is calculated from the product between critical current density and applied magnetic flux density. The magnetization curves were measured at 4.2 K. DC susceptibility of each sample was measured from 8.0 to 20 K in an applied magnetic field of 1.0 mT, after the sample had been cooled to 8.0 K (below the critical temperature, about 9 K, of Nb matrix) from room temperature.

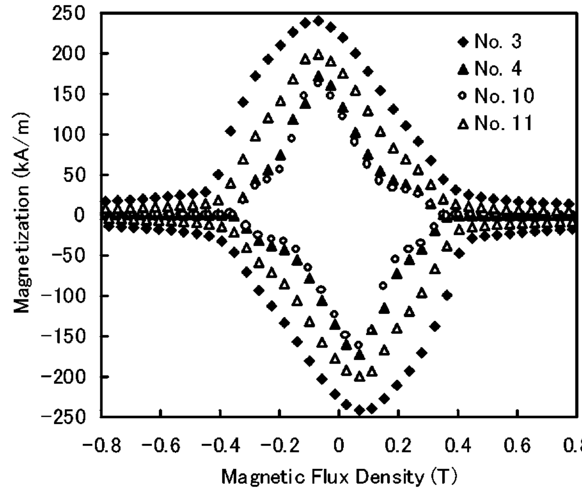


Fig. 4. Magnetization curves for various segments of sample YI2000D.

## III. Results and Discussion

### A. Heating Temperature During Rapid Heating

The heating temperature curves for the sample surface during rapid heating are shown in Figs. 2 and 3. The temperature at the center of a sample is not monitored after its temperature has reached the maximum temperatures, because of sample motion. A four-digit-number in the sample name shows maximum temperature $T_{\max}$ (°C) during rapid heating for each sample. The heating time from room temperature to $T_{\max}$ is within a range of 0.30 to 0.35 seconds as shown in Fig. 2. Supersaturated bcc-solid-solution Nb(Al)ss is obtained in the samples with $T_{\max}$ of 2000 °C or greater [5]. The heating time variation of from 0.26 to 1.14 seconds has been obtained by voltage control of the autotransformer in the equipment.

### B. Magnetization Curves After Rapid Heating

A 7.5 mm length was cut from both ends of sample YI2000D after rapid heating to 2000 °C and the middle part was cut in 11 segments 5 mm length. These segments were consecutively numbered no. 1 to no. 13 from the lower end, and the

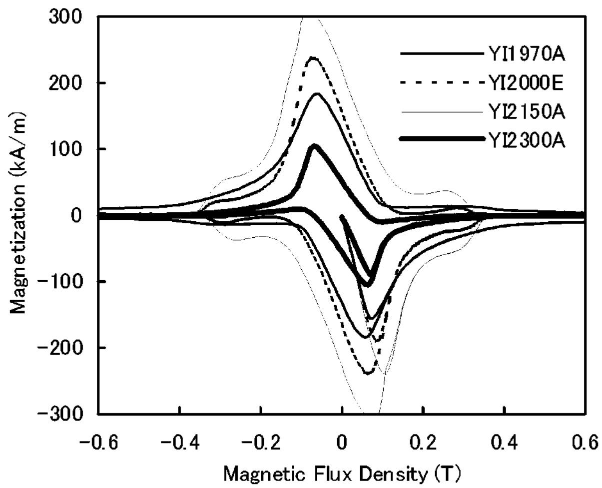


Fig. 5. Sample magnetization curves for various maximum temperatures.

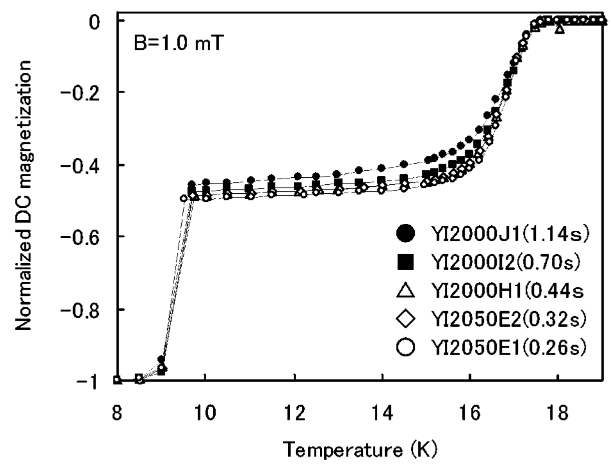


Fig. 7. Temperature dependence of normalized DC magnetizations in samples with various heating times.

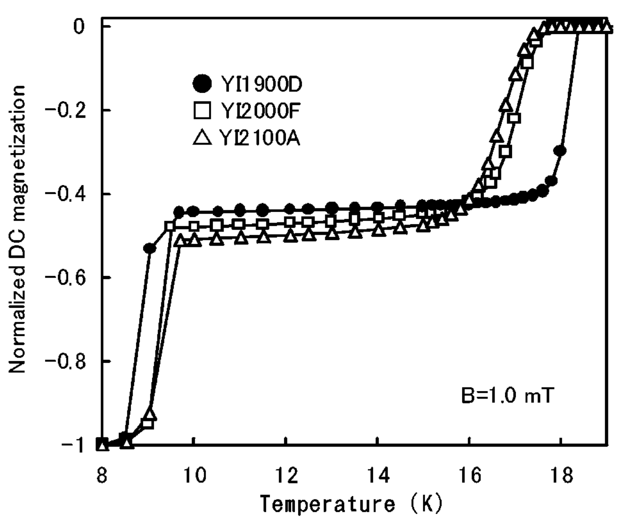


Fig. 6. Temperature dependences of normalized DC magnetizations in samples with various maximum temperatures.

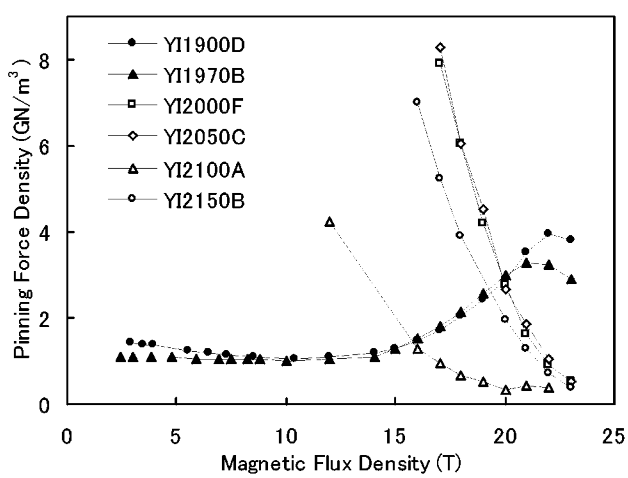


Fig. 8. Magnetic field dependence of pinning force density in samples with various maximum temperatures, $T_{\max}$.

magnetization curve of each part was measured at 4.2 K. The magnetization curves of typical segments are shown in Fig. 4. In this figure, a similar shape of magnetization curve is obtained on a 35 mm region (segments from no. 4 to no. 10). The upper and lower parts of this region show magnetization signatures of an A15-phase that has formed after rapid heating. Moreover, both the upper part no. 1 (crimped electrode) and the end part no. 13 (soaked in liquid gallium) were barely heated during the rapid heating and show the magnetization signature of Nb. In the sample heated to 2000 °C, a length of 35 mm multifilamentary region changes to bcc-solid-solution Nb(Al) in this rapid heating and quenching equipment. In the case of changing $T_{\max}$, the magnetization curves in the samples after rapid heating and quenching are shown in Fig. 5. These properties change at 2000 °C. The samples heated at 2000 °C or greater have upper critical fields of about 0.4 T.

## C. Temperature Dependence of DC Magnetization

Temperature dependencies of magnetization in these two series of samples are shown in Figs. 6 and 7, respectively. In these figures the samples have been annealed for 10 hours at 800 °C after rapid heating, and the magnetization of vertical axis is normalized by the magnetization at 8.0 K. The remarkable increase in the normalized magnetization at 9 K shows the transition of the Nb matrix. The samples that have an A15-phase by reaction between Nb and Al, during rapid heating, are characterized by both a sharp transition in temperature dependence and a rising of 1 K in critical temperature. On the other hand, the samples that have formed the supersaturated bcc-solid-solution Nb(Al)ss, after rapid heating and quenching, show a critical temperature of 17.3 K after annealing at 800 °C. The absolute values of normalized magnetization at 10 to 15 K increase with an increase in $T_{\max}$ as shown in Fig. 6. This result would be related to the increase of the reaction region between the jelly-roll

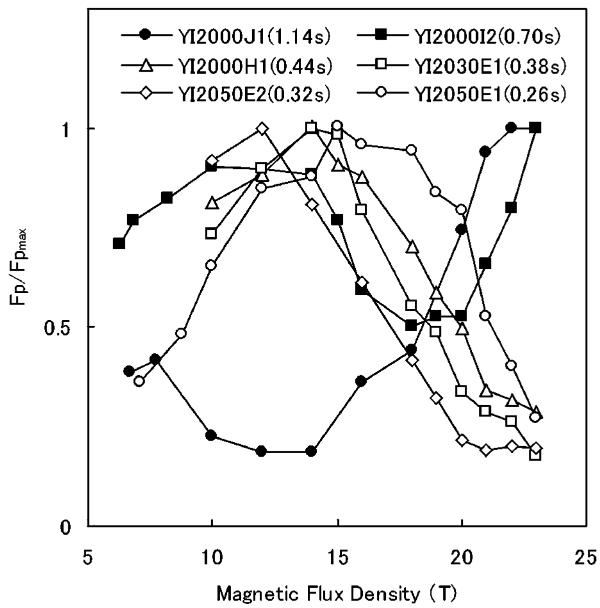


Fig. 9. Magnetic field dependence of normalized pinning force density, $Fp/Fp_{\max}$, in samples with various heating times.

and the Nb matrix with increasing $T_{\max}$. The samples with various heating times are compared in Fig. 7. In these samples $T_{\max}$ has been controlled between 2000 to 2050 °C. In the samples with heating times from 0.26 to 0.70 sec, these transition curves are approximately same.

### D. Magnetic Field Dependence of Pinning Force Density

As the maximum temperature during rapid heating is varied from 1900 to 2300 °C, the magnetic field dependence of $Fp$ falls into two groups, as shown in Fig. 8 [5]. On the other hand, samples with short heating times from 0.26 to 0.44 sec, shown in Fig. 9, have a peak between the magnetic fields of 12 to 15 T (open symbols), and shows a monotonous decreasing with an increase in magnetic field. In samples with long heating times the pinning force density increases with an increase in magnetic field, with a maximum at 20 T or more (closed symbols). For the sample with 0.70 sec heating time the curve indicates two peaks. If the variation of these properties is explained, it may be possible to improve pinning force density and critical current at high magnetic fields.

## IV. Summary

Two series of samples of jelly-roll $Nb_3Al$ multifilamentary wire were prepared by using the rapid heating quenching in conjunction with a noncontact temperature measurement technique. In short samples of 70 mm, homogeneity was evaluated by DC magnetization measurement, and a region of 35 mm was found to be approximately homogeneous. The absolute values of normalized magnetization at 10 to 15 K increase with an increase in maximum temperature, $T_{\max}$. This result would be related to the increase of the reaction region between jelly-rolled and the Nb matrix with increasing $T_{\max}$. The magnetic field dependences of $Fp$ can be divided into two groups (against various maximum temperatures or various heating time). The samples with a short heating times from 0.26 to 0.44 sec have a peak at a magnetic field of 12 to 15 T. On the other hand, in samples with long heating times, $Fp$ increases with an increase in magnetic field.

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