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Superconducting Properties and Rapid Heating Condition in Transformed Jelly-Roll Nb_3Al Multifilamentary Wires as a Function of Maximum Ohmic-Heating Temperature

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***Abstract*— Jelly-roll Nb_3Al wires with a Nb matrix were ohmically-heated to maximum temperatures ranging from 1800 to 2300 ℃ in vacuum in order to optimize the ohmic-heating conditions and to investigate the superconducting properties for this transformation method. The diameters of these wires were 0.80-1.34 mm. Surface temperature at the central point of the sample was measured by a photodiode during rapid ohmic-heating. After the surface temperature reached a maximum, the sample was quenched in liquid gallium. All the samples were annealed at 800 ℃ for 3-25 hours after the rapid heating process to transform the bcc-phase to the A15 phase. Critical currents were measured up to 23 T. The samples heated to 2000 ℃ showed a maximum critical current density of 64 A/mm^2 at 20 T. The critical current density decreased with increasing maximum temperature during rapid heating. This paper describes the superconducting properties, the rapid heating conditions and the achievement of high critical current density at high magnetic fields.**

***Index Terms*—Superconducting materials, niobium aluminum, ohmic heating**

I. INTRODUCTION

Nb_3Al has a high upper critical field at 4.2 K and a relatively small critical current degradation with increasing mechanical strain as compared to Nb_3Sn. New multifilamentary wires have been developed for high field NMR magnets and for high energy physics dipole magnets. The superconducting properties in Nb_3Al, which has an A15 crystal structure, are sensitive to compositional variation. To form the stoichiometric composition in the A15-phase, a rapid quench from the stable region at high temperatures [1] 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 [2], [3]. The rapid ohmic-heating and quenching method has been developed to realize this technique. Understanding the variation of the superconducting properties as a function of the maximum heat treatment temperature in jelly-roll Nb_3Al wire is important for the optimization of the rapid heating conditions.

In this study the samples were monitored using a non-contact measurement technique employing a photodiode [4]-[7] to measure high temperature (over 2000 ℃) during the rapid heating. The superconducting properties (such as critical field, critical temperature and critical current) were them explored as a function of maximum ohmic-heating temperature.

II. EXPERIMENTS

A. Samples

Three kinds of jelly-roll Nb_3Al multifilamentary wires have been prepared by drawing the same precursor to different final wire diameter. The wires of 0.80 mm, 0.94 mm and 1.34 mm diameter are named "YJ", "YI" and "YH", respectively. These wires consist of 54 filaments in a Nb matrix and the filament diameter is 72 μm in the YJ wire [4]. Fig.1 shows the basic circuit diagram of the heating and quenching system. The secondary current (to flow into the sample) increased by using a transformer [5]. A sample 70 mm in length is placed in a vertical direction. The 10 mm top part is crimped in a

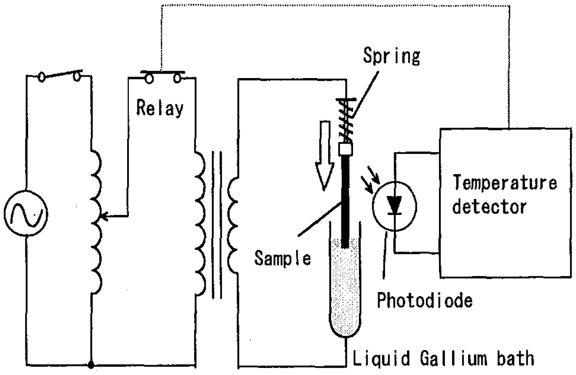

Fig. 1. Basic circuit diagram of the rapid heating and quenching system.

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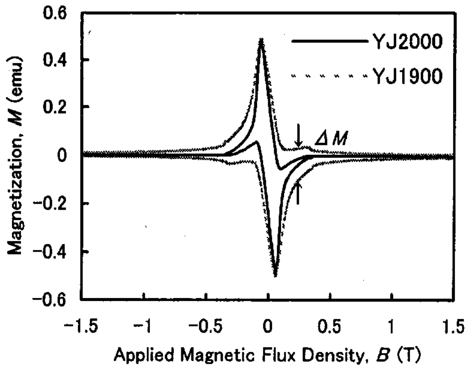

Fig. 2. Magnetization curves at 4.2 K of the samples after rapid heating.

movable electrode and the 10 mm end part was soaked in a liquid gallium bath. During rapid heating an alternating current flows between the electrode and the liquid gallium bath. Immediately when the temperature of the sample reaches the maximum set temperature, the sample is quenched in the liquid gallium. The maximum temperature, *Tm*, of the rapid heating was varied in a range from 1800 to 2300 ℃. The surface temperature at the center part of the sample was measured by a photodiode. The sampling time was 20 ms in this system. The radiance temperature was calibrated with an optical pyrometer and was determined from the voltage generated by the photodiode. The true temperature was calculated from the radiance temperature. After the rapid heating, all samples were annealed at 800 ℃ in vacuum to form Nb_3Al and to order the A15 phase. The annealing time was varied from 3 to 25 hours. The 10 hour-annealed samples were used for comparisons of critical current density against maximum temperature. In this paper the four-digit numbers in each sample-name expresses the maximum temperature, *Tm* (℃).

B. Measurements of Superconducting Properties

Critical currents, *Ic*, in 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 perpendicular to the longitudinal direction of the copper plated sample. The samples were measured by a four-probe method, with the voltage taps separated by 5 mm. The *Ic* criterion was 10 μV/cm. The critical current density, *Jc*, was defined as *Ic* divided by the jelly-rolled region of the precursor. The pinning force density, *Fp*, is calculated from the product between *Jc* and applied magnetic flux density *B*. The magnetization curves at 4.2 K and the temperature dependences of the magnetization were measured for the samples after rapid heating and subsequent annealing. Tc_{on} was determined from the temperature dependence of the magnetization.

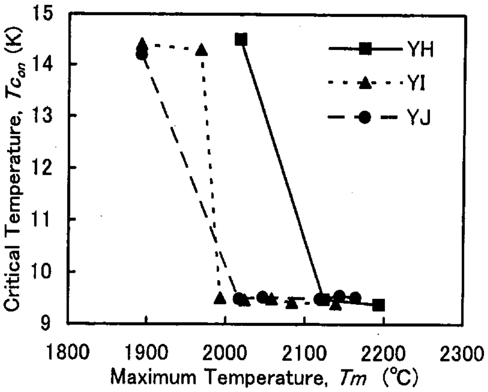

Fig. 3. Critical temperature after rapid heating versus maximum temperature.

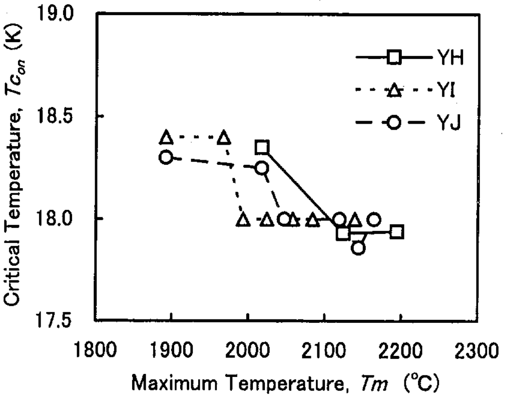

Fig. 4. Critical temperature after 800 ℃ annealing versus maximum temperature.

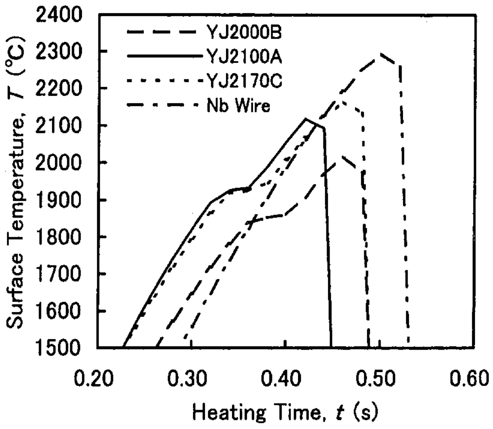

Fig. 5. Temperature curves on the sample surface at rapid heating.

III. RESULTS AND DISCUSSIONS

A. Critical Temperature and Magnetization Properties

After rapid heating the samples have two kinds of magnetization curves at 4.2 K as shown in Fig.2. YJ2000 has magnetization curves like a type II superconductor such as a pure Nb with low critical current density and a low B_{c2}. On the other hand, YJ1900 has a Bc_2 which is larger than 1.5 T, and a ΔM which is larger than that of YJ2000. The magnetization curves for the YJ samples heated above 2000 ℃ show the same shape. The samples of each wire are classified by two types of magnetization separated by a "boundary" maximum rapid heating temperature.

Fig.3 summarizes the critical temperature onset, Tc_{on}, against the maximum temperature, Tm, obtained during rapid heating. The samples with a critical temperature of 9.4-9.5 K show the same magnetization curve as the curve of YJ2000. The samples with a Tc_{on} over 14 K show a magnetization curve that is the same as the curve of YJ1900 in Fig.2. Tc_{on} after the annealing of 800 ℃ is plotted as a function of maximum temperature in Fig.4. In all samples Tc_{on} rises up to 17.9-18.2 K after annealing at 800 ℃. In the samples to be transformed to the A15-phase during rapid heating Tc_{on} is higher than that of bcc quenched samples.

B. Temperature Rise during Rapid Heating

Fig.5 shows the temperature curves during rapid heating of the YJ wire. The rapid heating time is 0.4-0.5 seconds from room temperature to maximum temperature, Tm. The average heating rate is 4000 ℃/s from 1500 to 1900 ℃. The curve for a pure Nb wire of 0.8 mm diameter is presented in Fig.5 for comparison with the jelly-rolled samples. The temperature of the Nb wire is monotonically increasing but the jelly-rolled samples have a minimum heating-rate up to Tm. These heating rates are plotted against surface temperature in Fig.6. In the Nb wire the heating rate is gradually decreasing with increasing temperature. On the other hand, in the YJ samples the heating rate dropped to 300-500 ℃/s at 1850-1950 ℃. The temperature, Tb, at the minimum heating rate is close to the melting point of Nb_3Al (1940 ℃). In all the samples quenched at a temperature over Tb, Tc_{on} have about 9.4 K and the magnetization curves are as same as that of a quenched pure Nb wire. Therefore the supersaturated bcc-phase is considered to be due to the phase change of Nb_3Al formed during the rapid heating. Fig.7 shows Tb in the three wire types against heating rate, dT/dt, at 1700 ℃ just before Tb. Tb shows on increasing tendency versus the increase of heating rate in each sample. The temperature that is shifted from 14 K to 9 K on Tc_{on} increases with increasing wire diameter as shown in Fig.3. These results indicate that the surface temperature is higher than the inside temperature because of the latent heat of Nb_3Al to be formed in the filamentary region.

C. Maximum Temperature Dependencies of Jc and Fp

The critical current densities at 17 T are plotted against annealing time at 800 ℃ in Fig.8. In this figure the YJ and

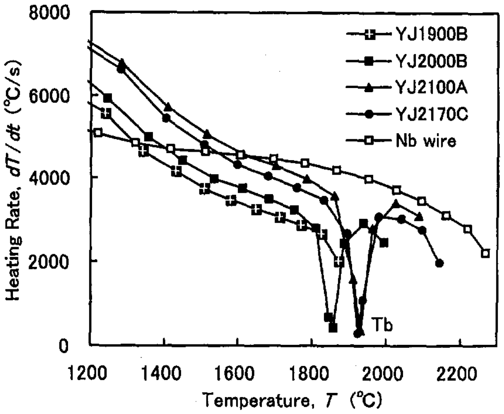

Fig. 6. Heating rates of the temperature on the sample surface at rapid heating.

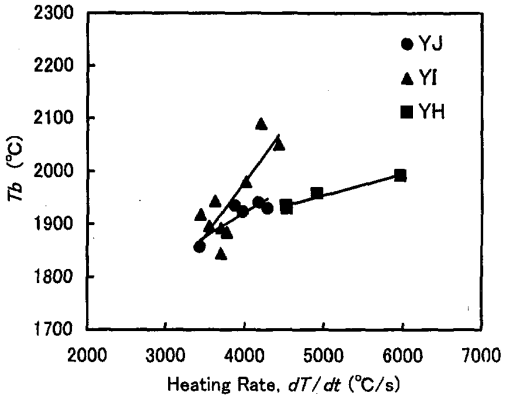

Fig. 7. Temperature at minimum heating rate versus heating rate at 1700 ℃.

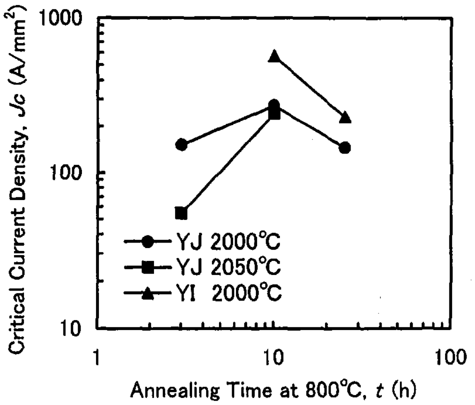

Fig. 8. Critical current density at 17 T, 4.2 K as function of the annealing time.

YI wires have been heated at 2000-2050 ℃ and a maximum *Jc* occurs at about 10 hours reaction at 800 ℃. Fig.9 shows *Jc* at 17 T in each sample after annealing for 10 hours at 800 ℃. In this figure the unfilled symbols show the sample that formed the A15-phase directly during rapid heating. The *Jc* values in these samples are approximately the same, (120 A/mm^2), and do not depend on the wire diameter. On the other hand, the solid symbols show the sample transformed to A15-phase after annealing. The maximum critical current densities are obtained at 2000 ℃ in the YJ wire and at 2050 ℃ in the YI wire. Therefore at a rapid heating time of 0.4-0.5 second the maximum *Jc* is obtained at 2000-2050 ℃, which is over the melting point of Nb_3Al, and Jc drastically decreases by increasing the maximum temperature over 2100 ℃. Since the maximum *Jc* of the YI wire is twice as large as that of the YJ wire, the optimization for the heating condition can be related to the microstructure in the precursor as well as the heating time and the maximum temperature.

The pinning force densities of the YJ wire are shown in Fig.10. The magnetic field dependences of *Fp* can be divided into two groups. The samples, such as YJ1900A, which formed the A15-phase during rapid heating, have a peak at high magnetic fields. Since these properties at high field show the same magnetic field dependence in the slow cooling samples using the same jelly-rolled precursor [4], the results suggests a grain growth during rapid heating in the samples below 1900-1950 ℃.

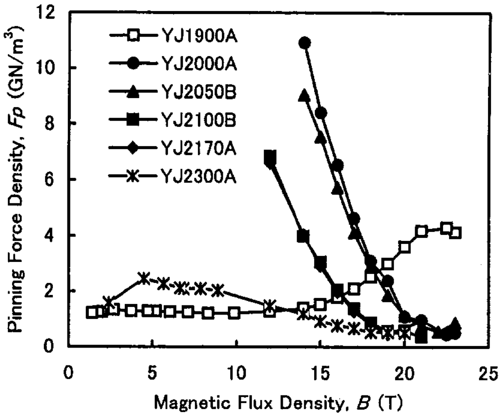

Fig. 10. Magnetic field dependence of the pinning force density.

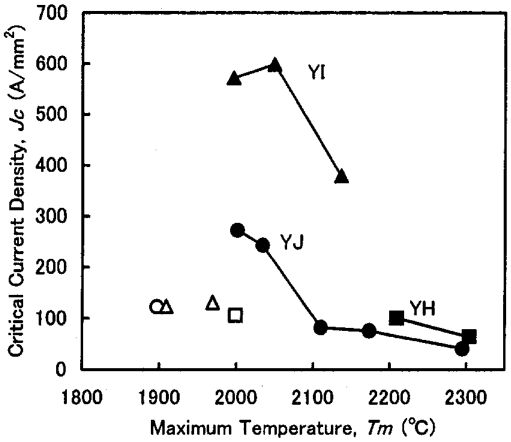

Fig. 9. Critical current density at 17 T versus the maximum temperature.

IV. SUMMARY

Superconducting properties in jelly-roll Nb_3Al wires have been compared with the maximum rapid heating temperatures in order to optimize the heating condition. Samples of each wire exhibit two different types of magnetization curves selected by being above or below a certain "boundary maximum temperature" during rapid heating, and the boundary temperature is increased with increasing wire diameter. In the YJ and YI wires the maximum critical current densities are obtained for a *Tm* in the range of 2000-2050 ℃, and are decreased with an increase in *Tm*. A peak effect at high field is shown by the samples that go to A15-phase after rapid heating. The supersaturated bcc-phase after quenching is considered to be due to the phase change at a temperature over the melting point of Nb_3Al. The surface temperature at the rapid heating is higher than the inside temperature, because of the latent heat of Nb_3Al in the filamentary region.

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