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Properties of Nb_3Al wires processed by double rapid heating and quenching

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Abstract

We have been developing Nb_3Al wires processed by rapid heating and quenching for a number of years as promising candidates for use in future high-field accelerator magnets. These wires have better strain and stress tolerances than Nb_3Sn wires do, but to meet the demands of future accelerator magnet designs, it is necessary to further improve their performance. In particular, it is necessary to increase their non-copper critical current density in 12-20 T fields. To pursue this goal, we introduced double rapid heating and quenching (DRHQ) treatment into the fabrication process for Nb_3Al wires, and studied the mechanical and superconducting properties of the resulting DRHQ-processed wires.

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Keywords: Nb_3Al wire; critical current; double rapid heating and quenching process; magnetization

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1. Introduction

Rapid heating, quenching, and transformation (RHQT)-processed Nb_3Al wires [1] have a better strain and stress tolerance than Nb_3Sn wires do [2,3], and exhibit promising high-field J_c properties. Therefore, these conductors may be promising candidates for use in future high-field accelerator magnets. For this reason, we have been developing RHQT-processed Nb_3Al conductors for a number of years. During this development, Ta-matrix Nb_3Al wire was developed to reduce the low-field instability that was observed in ordinary Nb-matrix Nb_3Al wires [4–6], and the trial fabrication of Nb_3Al Rutherford cables has also been carried out in collaboration with Fermilab [7,8]. However, the current state-of-the-art Nb_3Al wire has a lower critical current density than RRP Nb_3Sn wires [9] used recently for the development of high-field accelerator magnets. Therefore, it is necessary to increase the non-copper critical current density (J_c) of the Nb_3Al wires for use in high-field accelerator magnets. To pursue this goal, we have introduced the double rapid heating and quenching (DRHQ) treatment into the fabrication process for Nb_3Al wires. In conventional single-RHQ-processed wires, the filament materials become supersaturated bcc solid solutions during the RHQ treatment, and then the bcc phase filaments change to the A-15 phase during the transformation heat treatment at 800°C for ~10 hours.

The first trial DRHQ treatment of Nb_3Al wire was performed more than ten years ago at the National Institute for Materials Science in Japan [10]. In this study, the second RHQ treatment was used to transform the phase to A15-Nb_3Al after the first RHQ treatment for the synthesis of the Nb-Al supersaturated bcc solid solutions, and it was found that the DRHQ process was effective in improving the high-field (greater than 20 T) properties of Nb_3Al wires. However, the J_c of the DRHQ-processed wire in fields below 20 T was not as good as that of the conventional single-RHQ-processed wire. Furthermore, it is not easy to utilize this process in real Nb_3Al coil fabrication, since the filament materials of the DRHQ-processed wire have already transformed to the brittle A15 phase. Therefore, we investigated other conditions under which the filament materials remain in the bcc phase even after the DRHQ treatment.

2. Sample preparation

2.1. Precursor wire preparation

Multifilament precursor wire was fabricated using the jelly-roll process at Hitachi Cable, Ltd. (currently SH Copper Products Co., Ltd.). The initial monofilament wire was prepared by rolling Nb and Al foils around a Nb core and then wrapped with Nb foil, which eventually became the barrier between adjacent filaments. This process was followed by extrusion and drawing. The monofilament wires and Nb dummy core wires were assembled and wrapped with Nb sheet, which became the skin of the multifilament precursor wire. They were then stacked into a Cu-Ni alloy can to make a multifilament billet with a diameter of ~60 mm. The billet was extruded and drawn into a wire with a diameter of approximately 1.5 mm, and the Cu-Ni sheath was etched off for the RHQ treatment. The main parameters of the precursor wire are listed in Table 1, and the cross section is shown in Fig. 1.

Table 1. Precursor wire parameters.

Wire diameter (mm)	1.13
Matrix material	Nb
Matrix ratio	0.8
Filament diameter (μm)	74
Filament spacing (μm)	6
Number of filaments	132

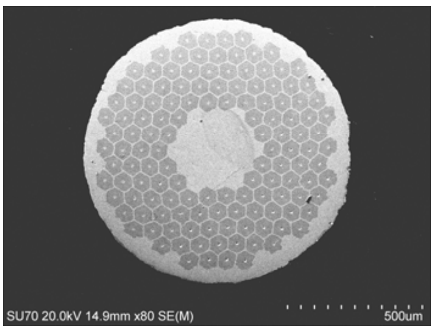

Fig. 1. Cross section of precursor wire.

2.2. RHQ treatment

The first RHQ treatment was performed on precursor wire with a diameter of 1.13 mm. In this treatment, a precursor wire moving at a speed of 0.3 m/s was continuously heated to about 2000 °C by Ohmic heating for about 0.4 s, and subsequently quenched in a molten Ga bath. The DC power supply for heating the wire was operated in constant voltage mode [11]. The voltage of the RHQ treatment (V_{RHQ}) selected for the first RHQ treatment was 10.1 V, which is almost in the center of the voltage region where supersaturated bcc solid solution filaments can be made. Next, the diameter of the wire was reduced to 1.0 mm by die drawing, and then the second RHQ treatment was performed under the same conditions as the first RHQ treatment, except for the RHQ voltages. The RHQ voltages suitable for producing bcc-phase filaments in the second RHQ treatment were studied using trial-and-error, and the results are shown in Fig. 2. Based on these results, three types of samples, treated at V_{RHQ}=11.8 V, 12.1 V, and 12.4 V, were prepared for this study.

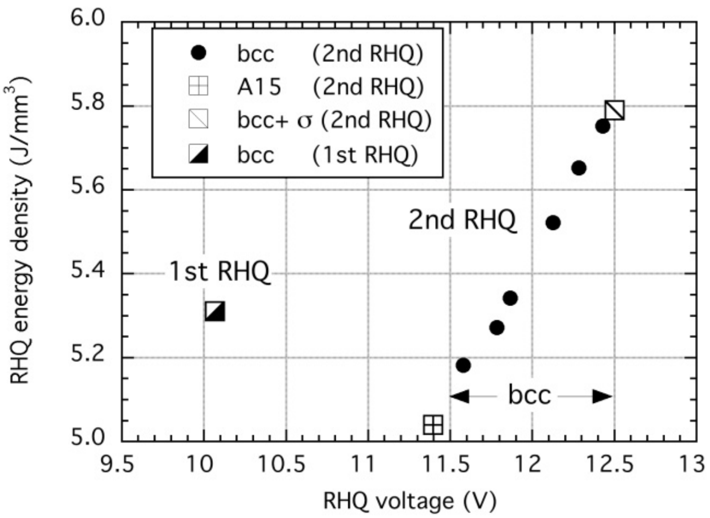

Fig. 2. RHQ energy density vs. RHQ voltage for the second RHQ treatment. The region in which the filament materials are in the bcc phase after the second RHQ treatment, as well as the first RHQ treatment conditions, are shown.

3. Experimental details and results

3.1. Mechanical properties

In the fabrication process for Nb_3Al wire, we usually use an area reduction (AR) process on the wire after the RHQ treatment to increase the J_c properties of the wires. Therefore, the workability of the RHQ processed wire is an important characteristic for actual fabrication. To measure this, the Vickers hardness was measured on the various parts of the cross-section of the DRHQ-processed wire.

The hardness values of the samples subjected to a second RHQ treatment (V_{RHQ}=12.1 V) and the area reduction process are shown in Fig. 3. Since the samples had experienced high-temperature annealing (~2000°C) during the second RHQ treatment, the skin and core of the samples were rather soft, but the filaments were fairly hard. The hardness of the skin and core stayed between 100 and 170 even after the AR processes, and that of the filaments was in the range of 490 to 510. The hardness values of the filaments after the second RHQ treatment are almost the same as those of the wires subjected to a conventional single RHQ treatment. This suggests that the mechanical properties of the bcc-NbAl are not affected by the synthetic route.

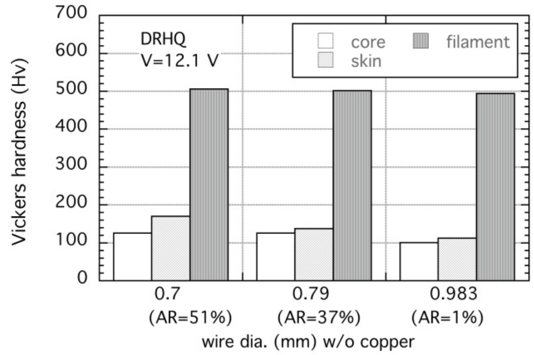

Fig. 3. Vickers hardness in various regions across the cross section of wires that were subjected to a second RHQ treatment and the area reduction process. The load applied to measure the hardness was 10 g.

3.2. Superconducting properties

The critical current (I_c) of samples which underwent single or double RHQ treatment were measured in a perpendicular magnetic field at 4.2 K. Samples of about 400 mm in length were wound in a helical groove on a stainless steel cylinder, and heat-treated at 800°C for 10 hours in a vacuum furnace. Subsequently, the reacted samples were transferred to an I_c measurement holder made of G10. Two voltage taps were soldered over the central 150 mm of the samples. The I_c of the sample was defined at a voltage of 3 μV (this correspond to a sensitivity of 20 μV/m), while the n-value was determined in the 10 to 40 μV/m range by fitting the V-I curve with the power law $V \sim I^n$. The estimated uncertainty of the I_c values is less than ±2%, and that of the n-values is about ±5. No self-field correction was applied in the determination of I_c.

Fig. 4 presents a plot of the critical current density J_c over the non-copper cross-sectional area of the DRHQ processed sample as a function of the applied magnetic field. The J_c of the samples whose cross sectional areas were reduced by around 36% after the second RHQ treatment is also plotted in the figure. The non-copper J_c values of the as-quenched samples (AR= 0%) were unexpectedly low, and the effect of the second RHQ voltage on J_c was very small. However, the J_c of the samples subjected to the AR process after DRHQ increased dramatically.

The n-values are plotted in Fig. 5 for the same samples, whose J_c values are shown in Fig. 4. Comparing Fig. 4 and Fig. 5, the following points become clear: (1) There is a clear correlation between J_c and n-value, i.e., samples with large J_c values have large n-values and vice versa. (2) The area reduction of the samples after the second RHQ

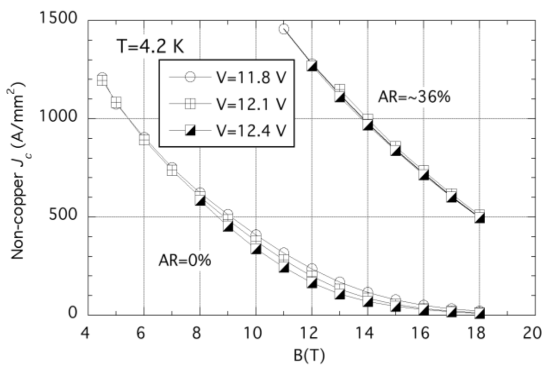

Fig. 4. Non-copper J_c of samples subjected to the second RHQ treatment. The voltage shown in the legend is the second RHQ voltage.

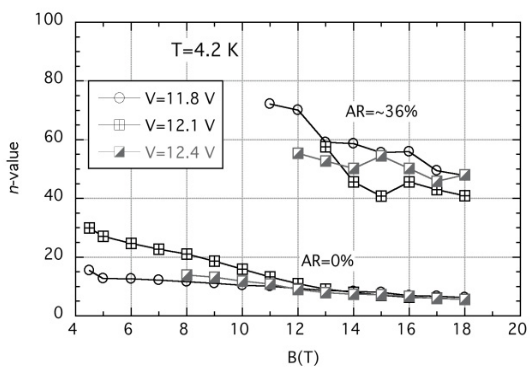

Fig. 5. n-values of samples subjected to the second RHQ treatment.

treatment is very effective in improving their J_c and n-values. A similar trend was observed for wires treated by the conventional single-RHQ processes, although the J_c increase is not as large as in this case.

Since it was found that AR is effective in improving the J_c properties of the samples even for DRHQ-processed wires, we studied the effect of AR on the J_c of the samples treated with various DRHQ voltages. Fig. 6 shows the results of this study, which demonstrate the following points: (1) When the AR level increases, J_c increases dramatically. When ~15% AR was applied to the samples, the J_c (15 T) values of the samples are about 14 times larger than those of the original (AR=0%) samples. (2) However, the improvement in J_c shows a saturation behavior when the AR levels become larger than 20%. (3) The highest non-copper J_c (~860 A/mm^2 at 15 T and 4.2 K) was obtained for the samples with ~36% AR. (4) With regard to the J_c value, 50% AR seems to be too much, and produces a small decrease in J_c from the highest values.

Fig. 7 shows typical variations of the n-values with AR. Until AR reaches about 40%, the n-values of all samples increase with AR, but some of them decrease slightly at 50% AR. This might be caused by irregular deformation or/and breakage of the filaments due to the greater reduction of the diameters.

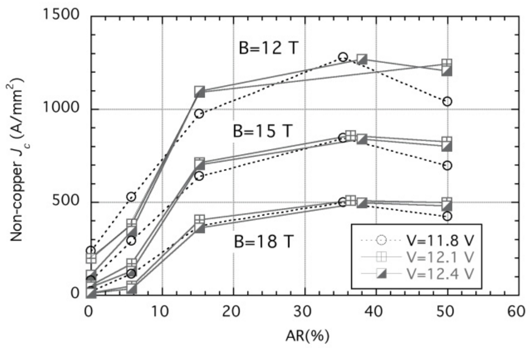

Fig. 6. Variation of non-copper J_c as a function of the area reduction after the second RHQ treatment. The voltages shown in the legend are the second RHQ voltages.

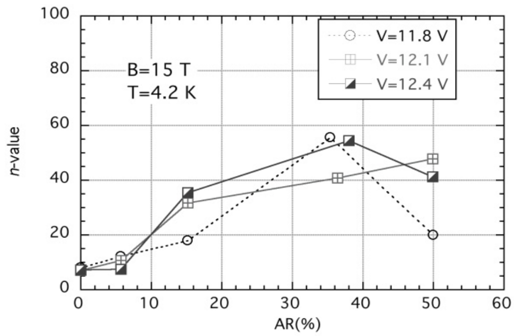

Fig. 7. Variation of n-values as a function of the area reduction after the second RHQ treatment.

Fig. 8 shows a comparison between the non-copper J_c values of single-RHQ- and DRHQ-processed samples. With regard to the J_c value, the effectiveness of DRHQ treatment is not obvious. However one can see a tendency for the samples treated by the DRHQ process to have slightly better high-field J_c properties than do the single-RHQ-processed samples.

Fig. 9 shows the normalized magnetic moment as a function of temperature for the DRHQ samples in a parallel field of 10 mT. The data for the conventional single-RHQ-processed sample are also shown for reference. From this

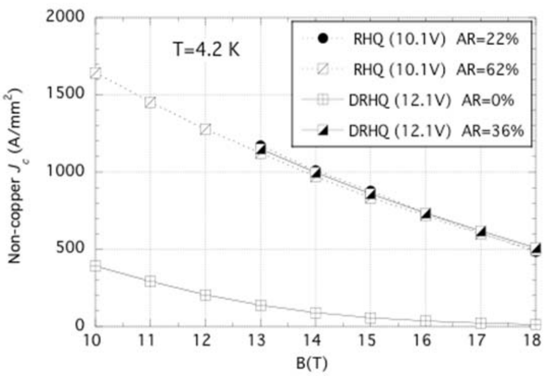

Fig. 8. Comparison between non-copper J_c values of conventional single-RHQ- and DRHQ-treated samples.

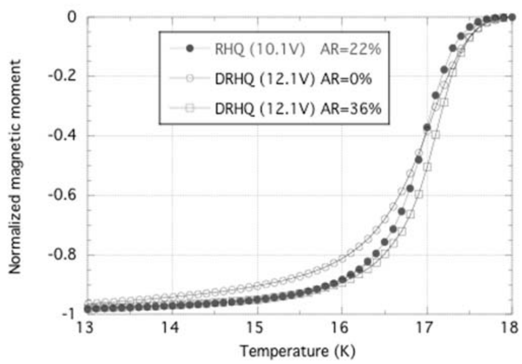

Fig. 9. Normalized magnetic moment as a function of temperature for single-RHQ and DRHQ samples. The magnetic moment was normalized by the moment value at 10 K.

figure, the following points become clear: (1) The T_c transition of the DRHQ sample with 0% AR is comparatively gradual, but it becomes sharper when the AR process is applied. (2) The T_c onset of the DRHQ sample with 36% AR is slightly higher than that of the single-RHQ sample with 22% AR.

4. Summary

Double rapid heating and quenching treatment was applied to multifilamentary NbAl precursor wires in order to improve their superconducting properties, and the properties of the resulting wires were investigated. We found rapid heating and quenching conditions suitable for producing bcc-phase filaments after the DRHQ treatment. However, most of the properties of the DRHQ-processed wires were very similar to those of the conventional single-RHQ-processed wires. An interesting finding of this study is that the J_c properties of the as-quenched DRHQ-processed sample are fairly different from those of the conventional single-RHQ-processed samples [12].

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References

[1] Takeuchi T et al. Status and perspective of the Nb3Al development. *Cryogenics*. 2008, vol. 48, p.371–380.

[2] Banno N, Uglietti D, Seeber B, Takeuchi T, Flükiger R. Strain dependence of superconducting characteristics in technical Nb_3Al superconductors. *Supercond. Sci. Technol*. 2005, vol. 18, p. 284–288.

[3] Kikuchi A *et al*. Cu stabilized Nb_3Al strands for the high field accelerator magnet. *IEEE Trans. Appl. Supercond.* 2008, vol. 18, p.1026–1030.

[4] Kikuchi A *et al*. Characteristics of Cu stabilized Nb_3Al strands with low Cu ratio. *IEEE Trans. Appl. Supercond.* 2009, vol. 19, p. 2678–2681.

[5] Tsuchiya K *et al*. Development of Ta-matrix Nb_3Al wire for next-generation accelerator magnet. *IEEE Trans. Appl. Supercond.* 2009. vol. 19, p. 2674–2677.

[6] Tsuchiya K *et al*. Magnetization studies of RHQT-processed Nb_3Al wires for high-field accelerator magnet applications. *J. Phys. Conf. Ser*. 2010, vol. 234, 022040.

[7] Kikuchi A *et al*. Strand and cable development for a high field Nb_3Al common coil magnet. *IEEE Trans. Appl. Supercond.* 2010, vol. 20, p.14284–1431.

[8] Tsuchiya K *et al.* Development of Ta-matrix Nb_3Al strand and cable for high-field accelerator magnet. *IEEE Trans. Appl. Supercond.* 2011, vol. 21, p. 2521–2524.

[9] Barzi E e*t al*. Studies of Nb_3Sn strands based on the Restacked-Rod Process for high field accelerator magnets. *IEEE Trans. Appl. Supercond.* 2012, vol. 22, 6001405.

[10] Kikuchi A. Iijima Y. Inoue K. Nb_3Al conductor fabricated by DRHQ (Double Rapidly-Heating/Quenching) Process. *IEEE Trans. Appl. Supercond.* 2001, vol. 11, p. 3968–3971.

[11] Banno N *et al*. Fabrication of long-length Nb_3Al wire by the metastable solid-solution-strand restacking method. *IEEE Trans. Appl. Supercond.* 2011, vol. 21, p. 2517–2520.

[12] Banno N, Takeuchi T, Tsuchiya K, Microstructural observation of transformed Nb_3Al superconductors using TEM and Atom Probe Tomography. *IEEE Trans. Appl. Supercond.* 2014, vol. 24, 8000104.