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Superconducting properties of internal-tin route Nb_3Sn wires with radially arranged filaments ☆ Development that realizes high J_c and low hysteresis loss

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Abstract

An internal-tin route Nb_3Sn superconducting wire that has both remarkably low hysteresis loss (Q_h) and high critical current density (J_c) was developed according to a new design idea. The wire was constructed by arranging the filaments in a radial layout, enlarging the outer filaments along the radial direction, narrowing the filament spacing in the radial direction intentionally and enlarging the filament spacing in tangential direction. Thus, the electromagnetic coupling among the filaments in tangential direction due to the bridging and/or proximity effect was suppressed without decreasing the volume fraction of Nb. As a result, excellent properties such as $J_c(12\ T) = 1.15 \times 10^3\ A/mm^2$ and $Q_h = 301\ mJ/cm^3$ (for 1 cycle of $B = \pm 3$ T) were obtained. We also evaluated the transition temperature (T_c) and upper critical field (B_{c2}) of the wire. The values for T_c and B_{c2} were 17.3 K and 24.1 T, respectively, which were much better than those of usual internal-tin route wires. Moreover, electron probe micro-analyses confirmed that the good T_c and B_{c2} were the result of the qualitative improvement of the Nb_3Sn compound based on the effects of arranging the Nb filaments radially, increasing the ratio of Sn-to-Nb and shortening the diffusion length for Sn. This wire is promising for use with conduction-cooled high-field magnets, in which there is a need to decrease the load of the cryocooler, and also for the strands of fusion coils.

Keywords: Nb_3Sn superconducting wires; High J_c; Low hysteresis loss; Internal-tin process; Radial arrangement

1. Introduction

At Mitsubishi Electric Corporation, various Nb_3Sn superconducting wires are being developed and manufactured by using an internal-tin process [1]. A merit of internal-tin route wires is that high critical current density (J_c) is easily obtainable, because it is possible to increase the amount of Sn compared with bronze route wires. For example, the wires used for dc magnets, which have no limitation on hysteresis loss (Q_h), have very high J_c over 1600 A/mm^2 under the following condition: applied field (B) of 12 T, temperature (T) of 4.2 K and expansive electromagnetic force applied to the wire [2]. We call these wires "high J_c type" hereafter. Note that J_c values hereafter are measured under these conditions unless otherwise specified. On the other hand, compared with bronze route wires, internal-tin route wires have a demerit regarding Q_h due to the narrow filament spacing and bridging caused by bronze formation during pre-heat-treatment. To deal with this demerit, the authors clarified the growth mechanism of the bridging among the filaments in our internal-tin route

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wires [3]. By controlling the Sn core-size and the filament spacing, we succeeded in manufacturing low Q_h wires with properties such as Q_h of 150–250 mJ/cm^3 (for 1 cycle of $B = \pm 3$ T; Q_h is calculated for the volume without the Cu stabilizer) and J_c of 750–850 A/mm^2 [4–6]. We refer to these wires as "low Q_h type" hereafter.

In the field of recently developed conduction-cooled magnets, both high J_c and low Q_h wires are required to generate a high field and to decrease the load on the cryo-cooler [7]. High J_c and low Q_h are also required for the strands of fusion coils [8]. We thus decided to develop a new internal-tin route wire. Being different from the "high J_c type" or "low Q_h type", it has a considerably low Q_h (approx. 500 mJ/cm^3) compared with the "high J_c type" and a high J_c (>1000 A/mm^2) close to that of the "high J_c type".

In this paper, the method of designing, the result of manufacturing, the evaluation results of some superconducting properties and consideration concerning the loss are discussed.

2. Design of new wire

In the case of designing a wire with $J_c = 1100$ A/mm^2 and $Q_h = 1500$ mJ/cm^3 which is not so high as that of the "high J_c type" described above, such wire design was adopted until now as both increasing the volume fraction of Nb and Sn to achieve $J_c = 1100$ A/mm^2 and enlarging the filament spacing as wide as possible to avoid loss increase due to the proximity effect. We call the wire fabricated by this design method HJT-1000 hereafter. Moreover, since it is impossible to avoid the generation of rings due to the bridging of each Nb_3Sn filament [3], we had to consider the filament arrangement to reduce the ring size as small as possible in order to achieve low Q_h. However, regarding the wire constitution, a trade-off exists between filament diameter and filament spacing. That is, because the ratio of filament diameter-to-filament spacing is uniquely determined as a certain value if the ratio of Cu-to-Nb is set in terms of volume fraction, except for the constitutionally necessary Cu that exists in the outermost part of the module (i.e. sub-element) and surrounding the Sn core. Meanwhile, since our target value for Q_h is not so severe compared with that of the "low Q_h type", some bridging among filaments is allowed for our design policy as long as Q_h does not become too large.

Therefore, we converted our design policy from avoiding the loss increase due to bridging and/or proximity effect (by making the filament spacing as large as possible) to a new concept; not only by arranging the filaments radially and enlarging the outer filaments along the radial direction but also by narrowing the filament spacing in the radial direction intentionally, we enlarge the filament spacing in the tangential direction. As a result of this design, the bridging and/or proximity effect in the tangential direction is suppressed and we can improve Q_h compared with that of conventional wires.

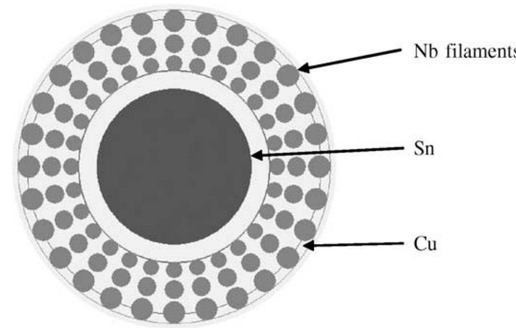

Fig. 1. Configuration of a new module with radially arranged filaments.

Applying this design concept, we designed a new wire composed of the module shown in Fig. 1. The features of the filament constitution for the wire are listed as follows:

(1) To make each filament in the radial direction combine intentionally, we arranged the filaments in a radial layout and narrowed the filament spacing in the radial direction (<0.5 μm).
(2) In the case that the filaments are arranged radially, the volume fraction of Nb decreases extremely if the filament size is set equally. Accordingly, we adopted a constitution in which the outer filaments have larger diameters along the radial direction.
(3) In the case of using several different filament diameters in one wire, it is a cause of concern that the composition of the formed Nb_3Sn compound might become inhomogeneous. To deal with this problem, we decreased the filament rows to three layers, and we adopted a wire constitution of 91 modules. Owing to this precaution, Q_h is expected to be suppressed even if the rings occur, because the size of the rings is kept small.
(4) We widened the filament spacing in the tangential direction (>1.0 μm) so as to avoid loss increase due to bridging and/or proximity effect.

3. Experimental procedure

The cross-sectional photograph of the new wire (sample R) before heat-treatment, which was fabricated according to the design concept mentioned above, is shown in Fig. 2, and its specifications are listed in Table 1. The specifications of sample HJT-1000 and the "low Q_h type" (sample KL), which are used to compare superconducting properties with sample R, are also listed in Table 1. The new wire showed good workability on trial, and we were able to obtain 1000 m-class wires. The manufacturing process of our internal-tin route Nb_3Sn wires is described in detail elsewhere [1]. As shown in this picture, the new wire is constructed with a superconducting region of 91 stacked modules composed of Nb filaments and Sn–1.6 wt.%Ti cores in a Cu matrix (see Fig. 1), a Ta barrier and a Cu stabilizer.