Insert model coil wound by Al203-Cu strengthened Nb3Sn wire

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Insert Model Coil Wound by Al_20_3-Cu Strengthened Nb_3Sn Wire

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***Abstract*----With the aim of fabricating large-bore, high-magnetic-field magnets with low coil weight and volume, an alumina-Cu reinforced Nb_3Sn wire of 1 km in length has been developed by improving the workability of the tube process. Two kind of insert model coils were made using the developed wire and the conventional Cu-matrix wire . The maximum quench current observed was 126 A in a backup field of 11 T, which corresponds to an electromagnetic force of 244 MPa. The coil strain for the reinforced coil was always smaller than that for the Cu-matrix coil.**

I. INTRODUCTION

High magnetic fields and current densities in magnets, exert electromagnetic forces on the current-carrying conductors, thus degrading their superconducting properties. A high field magnet with a large bore requires a superconducting wire with high mechanical strength and high current density.

To meet these demands, we have been developing an alumina dispersion-strengthened copper (alumina-Cu) reinforced Nb_3Sn wire using the tube process. We have previously reported on the mechanical and superconducting properties of reinforced Nb_3Sn composite wires with various contents of alumina-Cu in the whole volume of the wire instead of as a part of the Cu-matrix [1]-[2]. These wires exhibited high yield strength, high tensile stress tolerance, and high transverse compressive stress tolerance whose values are two or three times as high as those of the conventional Cu-matrix wire [3]. Moreover, we have succeeded in fabricating an alumina-Cu reinforced Nb_3Sn wire in lengths of the order of a kilometer [4].

Such a long wire enables us to demonstrate the good mechanical strength in a magnet. In this paper, we report on test results for a model coil with the alumina-Cu reinforced wire in a back-up magnetic field, and compare them with those for a coil fabricated with conventional Cu-matrix wire. The developed alumina-Cu reinforced Nb_3Sn wire proves to be very promising for the compact construction of lightweight, large-bore, high-magnetic field superconducting magnets.

II. ALUMINA-COPPER REINFORCED Nb_3Sn WIRE

A. *Deoxidization-Processed Alumina-Copper*

A selective deoxidization process gives both good mechanical strength and good electric conductivity after the formation of Nb_3Sn at approximately 700 °C was chosen. First, copper oxide and alumina powders were mixed as starting materials and pulverized to form a fine, homogeneous mixed powder in a large-capacity ball mill that could avoid contamination. The mixed powder was heat-treated in a H_2 atmosphere and the copper oxide was selectively deoxidized and continuously hot-pressed at around 900 °C. The resulting Cu-1.1% alumina ingot was extruded and drawn into rods and tubes at the high temperature of 850 - 900 °C to attain good elongation and ductility. These alumina-Cu tubes and rods were of sufficient quality and were obtained in sufficient large quantities for Nb_3Sn wires to be made.

B. Tube-Processed Nb_3Sn Composite Wire

The reinforced material, alumina—Cu, was co-reduced

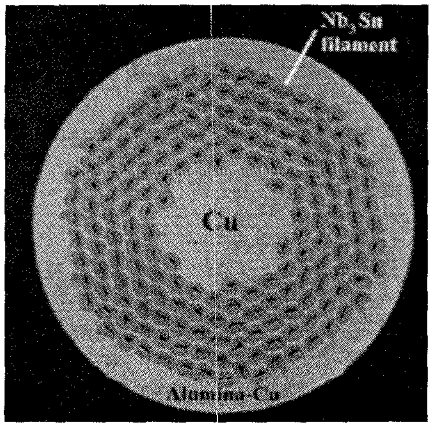

Fig. 1. Cross section of developed alumina-Cu reinforced Nb_3Sn wire

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with the Nb_3Sn wire using the tube process. We used the alumina-Cu tube to surround each Nb tube filament (containing 1%Ti) which includes a copper-sheathed tin-core inside. A copper tube surrounds a bundle of alumina-copper matrix and Nb filaments, which contains a copper core in the center of the composite wire, as shown in Fig.1. This structure was adopted to improve the ductility of the wire. The composite wire was drawn down to final size of 1 mm without intermediate annealing and was finally submitted to heat treatment at 720℃ for 50 h to form Nb_3Sn. The alumina-Cu reinforced composite wire was successfully fabricated to a length of about 1 km without any breakage. For comparison, an all Cu-matrix Nb_3Sn wire was also fabricated. A model coil was fabricated using 700 m of wire and the remainder of the wire was used for evaluation of short samples. Specifications of round cross sections of these wires are listed in Table I. A rectangular shaped wire (cross section: 1.4x2.2 mm) was also fabricated for mechanical property tests.

III. COIL DESIGN AND FABRICATION

Using a 700 m length of the 1 mm diameter reinforced wire, a model coil with an inner diameter of 238 mm, an outer diameter of 280 mm, and height of 50 mm was wound and impregnated with epoxy resin. The coil was not supported by an outer shell of stainless steel wire or similar material so as to enable accurate measurement of coil displacements during coil energizing [5]. Typical parameters for the model coil are listed in Table I.

TABLE I

PAPAMETERS FOR CONDUCTOR AND COIL

Conductor	
Wire diameter (mm)	1
Number of filament	180
Filament diameter (μm)	46
Filament composition	Nb-1%Ti
Matrix to non-matrix ratio	1.4
Volume fraction (%)	
non-matrix	42
Cu-matrix	33
alumina-Cu-matrix	25
Alumina content (%)	1.1
Coil	
Structure	impregnated layer winding
Inner diameter (mm)	238
Outer diameter (mm)	280
Coil height (mm)	50
Ampere turn (T/A)	0.004
Winding turns	830

Acoustic emission (AE) sensors were bonded to the top surface of the coil. Several sets of strain gauges were glued to the inner and outer surface in circumferential and axial directions. Three pairs of voltage taps were attached to the coil. These sensors were used to observe changes in coil deformation and quench current due to electromagnetic forces applied to the coil.

The coil was inserted and energized in a 300 mm bore under a backup field of 10-11 T to study the superconductivity in relation to mechanical properties. For comparison, a coil of the same size was prepared using the Cu-matrix Nb_3Sn wire.

IV. STRUCTURAL ANALYSIS

Internal stress in the coil due to cool down and energizing was calculated using the following model:

(1) The stress-strain characteristics for the conductors were considered to be linear.

(2) The coil consists of Nb_3Sn conductor and insulating (epoxy resin) layers and was regarded as a multi-layered cylinder.

The insulating layers of epoxy resin, were assumed to be elastic.

V. RESULTS AND DISCUSSION

A. *Mechanical and Superconducting Properties of the conductor*

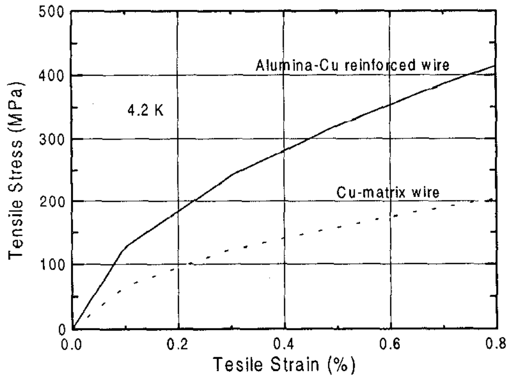

Fig. 2. Stress-strain curves at 4.2 K for alumina-Cu reinforced and Cu-matrix Nb_3Sn wires

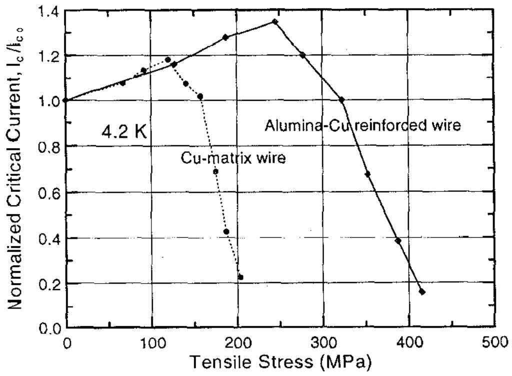

Fig. 3. I_c/I_{c0} as a function of tensile stress for alumina-Cu reinforced and Cu-matrix Nb_3Sn wires

Tensile tests were carried out at 4.2 K on short samples to obtain a stress-strain curve. The critical current (I_c) at 100 μV/m was measured at 4.2 K in a transverse magnetic field. The critical current density (J_c) was obtained by dividing I_c by the cross section of the non-matrix portion. The critical current as a function of tensile stress-strain was measured in a transverse magnetic filed of 13.5 T, applied parallel to the wide surface of a rectangular-shaped wire.

The stress-strain curve of alumina-Cu reinforced Nb_3Sn wire at 4.2 K is shown in Fig.2 together with that of the Cu-matrix wire. As the 0.2% off-set criterion to obtain the proof stress was not clearly determined in this case, tensile stress at 0.3% strain was applied as the proof stress. The average proof-stress (tensile stress at 0.3% strain) of the alumina-Cu reinforced samples was 221 MPa with a variation of 2.6%. The tensile stress at 0.3% strain for this reinforced wire was twice as large as that for the Cu-matrix, which was 114 MPa.

Good characteristics of Jc vs. magnetic field were obtained for both the alumina-Cu reinforced Nb_3Sn wire and Cu-matrix wire. The results were 640 A/mm^2 and 370 A/mm^2 at 15 and 17 T, respectively. The alumina-Cu reinforced Nb_3Sn exhibited approximately the same critical currents as the Cu-matrix wire.

The effects of tensile stress on normalized Ic (I_c/I_{c0}; I_{c0} at zero applied stress) at 13.5 T are shown in Fig. 3 for an alumina-Cu reinforced wire and a Cu-matrix wire with a rectangular cross section. For the alumina-Cu wire, I_c/I_{c0} increases with increasing tensile stress up to 230 MPa, and then decreases. It is greater than 1 up to 290 MPa, the critical tensile stress. The peak I_c/I_{c0} occurs at only 120 MPa and the critical tensile stress is 160 MPa for the Cu-matrix wire.

B. *Coil Training*

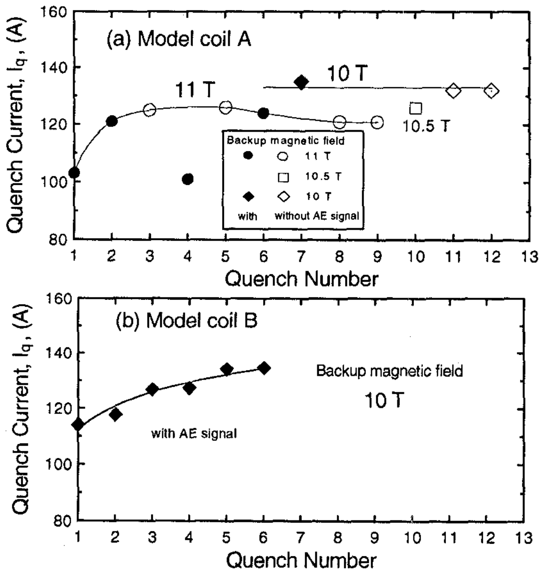

Fig. 4. Training of quench currents for (a) the model alumina-Cu reinforced Nb_3Sn coil (coil A), and (b) the reference coil of Cu-matrix wire (coil B).

The insert model coil (coil A) was energized in a backup magnetic field of 10 to 11 T, while the reference coil (coil B) of the Cu-matrix conductor was investigated in a 10 T field. Figure 4 shows the training of coil quench current, I_q, for (a) coil A and for (b) coil B. The quench current of coil A increased and reached 126 A at the third quench in a backup field of 11 T. This quench current of 126 A in a backup field of 11 T corresponds to an electromagnetic force of 244 MPa; this current was continuously held for 15 min. The closed symbols in Fig. 4. represent the appearance of a voltage spike and an AE burst in the quench. Almost all quenches occurred in the inner first layer of the coils. Since the quench currents of coil A depended little on the backup magnetic field, these quenches are not caused by the conductor's I_c. On the other hand, the quench current in coil B gradually increased and seemed to remain unsaturated over the experimental range.

C. *Stress Strain Curves for Coils*

Figure 5 shows the applied charging current dependence of strain for the inner surface of coil A; the solid line represents the calculated strain. The strain gauges were calibrated after cooling to 4.2 K, and the measured strain was caused only by charging. The data coincide well with the calculation.

Stress-strain curves during charging are shown for both

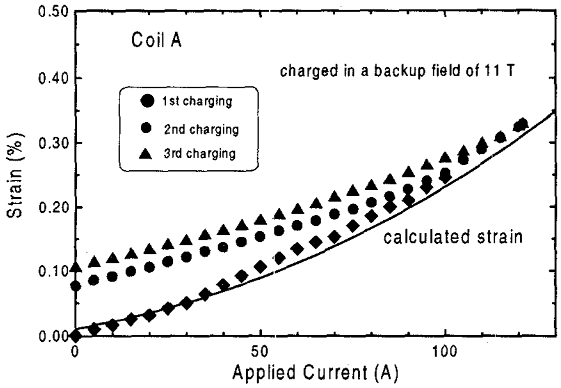

Fig. 5. Applied charging current dependence of strain at the inner surface of the coil A, where the solid line represents the calculated strain. The data coincide well with the calculated values.

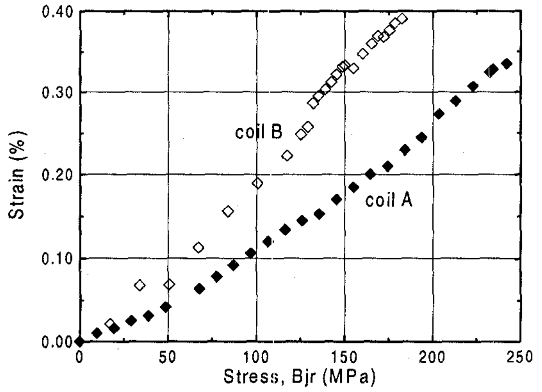

Fig. 6. Measured strain as a function of calculated stress in charging for both coils. The alumina-Cu reinforced coil always exhibits smaller strain than the Cu-matrix coil.

coils in Fig. 6. Stress was calculated from the electromagnetic force by B×j×r at the inner surface of the coil. The strain for coil A is always smaller than that for coil B. This data demonstrates that the alumina-Cu reinforced Nb_3Sn wire has excellent stress resistance even in coil form.

D. Load Line based on Strain Dependence of Critical Current for Conductor

The maximum quench current for the model coil is 126 A in a backup magnetic field of 11 T, where the electromagnetic force is estimated to be 244 MPa at the inner surface of the coil. Based on the magnetic field dependence of the critical current for the short sample, the maximum quench current for the coil might be 262 A as shown in Fig. 7. Note that the magnetic field dependence of the critical current for a short sample is measured in a residual prestrain state. Therefore, the effect of tensile stress or strain on the critical current should be taken into account in designing this type of coils.

Based on the data given in Fig. 3, we have obtained a relationship between I_c and tensile stress or strain for short samples. The bold line in Fig. 7 represents the magnetic field dependence of I_c for the coil in a backup field, reflecting the effect of tensile stress on I_c for short samples.

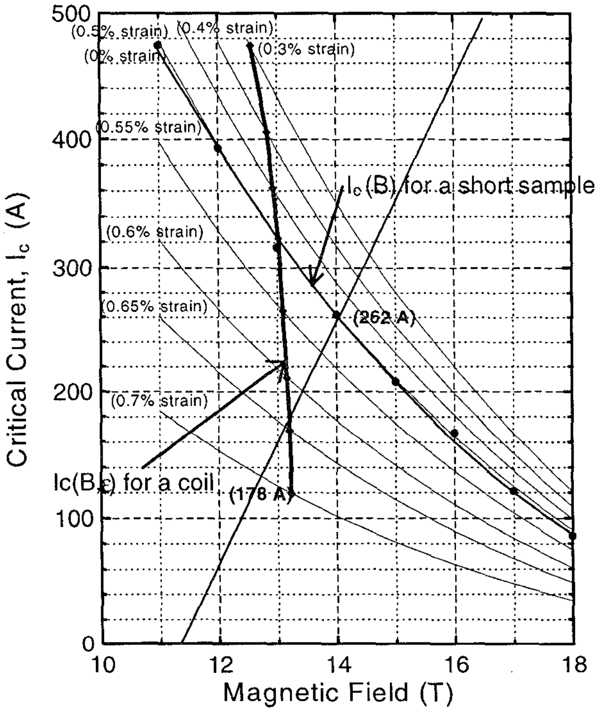

Fig. 7. Load line for alumina-Cu reinforced insert model coil

Using the I_c vs. B under stress, the maximum quench current attainable for this coil is estimated to be 178 A. Unfortunately, we did not observe such a high maximum quench current because some other parts aside from the coil winding were not strong enough for the electromagnetic force. The coil structure is to be reconsidered and another charging test is planned.

VI. CONCLUSION

To enable fabrication of large-bore, high-magnetic-field magnets with low coil weight and volume, an alumina-Cu reinforced Nb_3Sn wire of 1 km in length has been developed by improving the workability of the tube process. The reinforced wire exhibited excellent performance in superconducting and mechanical properties, and had a high tensile stress tolerance up to 300 MPa.

Two kind of insert model coils were fabricated using a developed wire and a conventional Cu-matrix wire. The maximum quench current observed was 126 A in a backup field of 11 T, which corresponded to an electromagnetic force of 244 MPa. The coil strain for the reinforced coil was always smaller than that for the Cu-matrix one.

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