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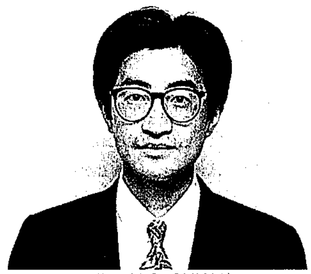
NbTi/Nb/Cu Multilayer Composite Materials for Superconducting Magnetic Shielding
– Superconducting Performances and Microstructure of NbTi Layers –





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Abstract

NbTi alloy is popularlized for practical uses of superconducting multifilamentary wires, and is utilized for MRI systems in large amounts. Those wires are effective as current conductors, but a superconductor consisting of a two-dimensional plane has been often referred to as a possibly better shield against electromagnetic fields than wires. In recent years, Nippon Steel Corp. has developed the superconducting multilayer composite sheet and cylinder consisting of NbTi alloy as a superconductor being clad with copper for superconducting stabilization. A sample consisting of four cup-like cylinders with a thickness of 1mm, which are concentrically stacked, can stably reduce the applied magnetic field of 2.6 tesla to less than 10 gauss. This paper describes their characteristics of the multilayer structure and fabricating processes, and as important superconducting properties, critical current densities(J_c), shielding properties of DC and AC magnetic fields, magnetic field homogenizing effects and new techniques for extremley increasing J_c in consideration of the internal microstructure of the NbTi layer. Finally, a few test results of the performances of the material provided by domestic and foreign organizations are also touched.

1. Introduction

Superconducting magnets have been successfully used in practical applications for such devices as MRI systems (medical diagnostic imaging system) and MCZs (Magnetic Czochralski method for silicon single crystal for semiconductors)[1] which are steadily expanding their market volumes. The technology is also crucial for the development of equipment such as particle accelerators, nuclear fusion systems, linear motorcars (MAGLEV), superconducting generators and so forth within Japan, which is earning a global reputation in this field. The trend in the development of superconducting magnets is toward higher magnetic field and larger storage energy. Under these circumstances, the leakage of magnetic field outside of

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the equipment will become an increasing problem, having negative effects upon human health and electronic devices[2]. Other crucial problems include electromagnetic noise from external fields which adversely affect the superconducting magnets or its internal spaces to be detected[3,4] and the fact that a highly homogeneous magnetic field is required inside superconducting magnets[2].

For the magnetic field shielding of these superconducting magnets, high permeability materials such as low carbon steel have been utilized in many cases as in MRI[2], though the weight of such materials has been a major hindrance in promoting the use of such materials in various applications. Recently, an active shielding method which utilizes superconducting wires has become popular as it reduces the weight. This method is very effective in DC magnetic field shielding for a fixed-direction magnetic field and can also provide high magnetic field shielding. However, the method is not suitable for shielding alternating magnetic fields and RF wave noises coming from many directions. Good electric conductors such as those made of copper, aluminum, etc. are effective in shielding alternating magnetic field and RF wave noises[3], though they have low performance in the case of a low-frequency magnetic field where there is no skin effect. On the other hand, an MRI require complicated placement of shim coils and steel pieces to achieve a highly homogeneous magnetic field[2].

It has been pointed out that superconductors with planar surfaces (including curved surfaces)[5-7] and cylindrical superconductors[8,9] are effective for shielding of such magnetic fields as noted above. Superconducting seamless cylinders, in particular, can shield in all directions provided that appropriate aspect ratios (axial length/diameter) are given, and so may effectively shield all of the magnetic field types mentioned above. The NbTi/Nb/Cu multilayer composite material which Nippon Steel Corp. has recently developed can be used for both planar and cylindrical superconductors[10,11]. The objectives in the development of the material are to secure practical J_c (critical current density) and superconducting stability, and to achieve a sufficiently large area of the multilayer sheet or a completely seamless and large cylinder for eliminating joints which shall cause magnetic field leakage. These are important requirements for a superconducting magnetic shield, and a manufacturing method suitable for industrial mass production needs to be developed.

Superconducting magnetic shielding in this context can be realized only if a loop of superconducting shielding current (permanent current) running through the superconductor is formed, and so joints which interfere with the formation of the loop must be eliminated wherever possible. The structural features, fabricating processes, magnetic shielding properties of this superconducting multilayer magnetic shielding material, and the relationship between the microstructure of NbTi and J_c are described below.

2. Structure and fabricating processes of multilayer composite material

This multilayer composite sheet has a multilayer structure in which NbTi and Cu layers are alternately laminated. A thin layer of Nb as the barrier to prevent Ti from diffusing into Cu due to the heat applied during the fabricating processes is inserted in each interface between NbTi and Cu, thus forming a three-layer structure in the sheet[10]. This multilayer composite sheet is fabricated by an airtight cladding and rolling method. **Fig. 1** shows the flow of the fabricating processes. NbTi sheets and Cu sheets of the desired dimensions are prepared, and are alternately laminated inside a prefabricated Cu box. Nb sheet is inserted in each interface between the NbTi sheet and Cu sheet. Next, a Cu-plate cover is attached on top of the Cu box to form a multilayer lamination. Then, the laminated structure is sealed airtight by electron beam welding in a vacuum. By hot rolling, the metallic layers inside are bonded into a united clad sheet, and finally

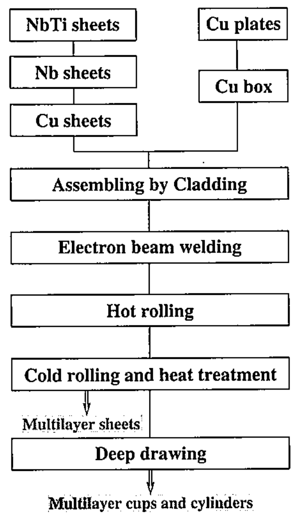


Fig. 1 Fabricating processes of multilayer composite sheets and cylinders

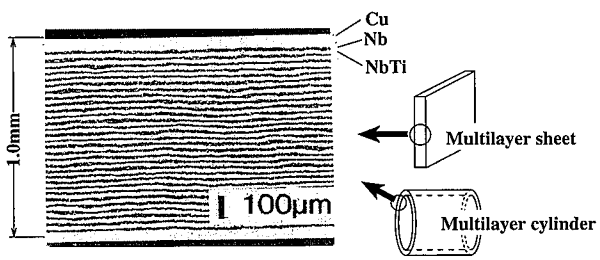
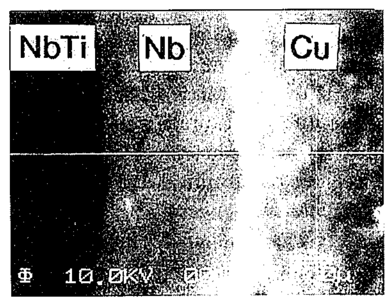
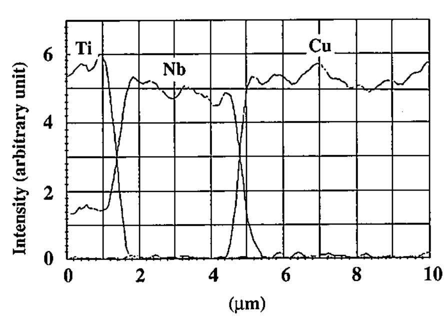


Fig. 2 Cross-sectional structure of multilayer sheet cylinder



(a) SEM cross-sectional photo of Nb barrier layer



(b) Positive effect to prevent Ti diffusion by AES line-analysis

Fig. 3 SEM cross-sectional photo of Nb barrier layer and its positive effect to prevent Ti diffusion by AES line-analysis

cold rolling and heat treatment are applied appropriately to produce the desired multilayer sheet. The multilayer sheet thus prepared has high formability and can be transformed into a seamless multilayer cylinder with a bottom by a deep drawing or spinning process, or into a seamless multilayer cylinder without a bottom by further cutting off of the bottom part[10,11].

Nb-46.5wt%Ti alloy ingot available commercially was used as NbTi raw material. NbTi sheets of the desired dimensions were prepared by hot forging the ingot followed by hot rolling and cold rolling. Commercially available four-9 pure Cu was used as the raw material. Commercially available Nb was also used as the raw material. **Fig. 2** shows a cross-sectional photo of the multilayer material having a thickness of 1 mm. **Fig. 3** shows an SEM photo of NbTi/Nb/Cu interfaces and the positive effect on preventing diffusion by AES line-analyzing. The multilayer sheet consists of 30 NbTi layers having a thickness of about 10 μm and 29 Cu layers having almost the same thickness as an NbTi layer except for the outermost Cu layers. The cross-sectional area ratio between Cu and NbTi is about 1.6[10].

3. Superconducting magnetic shielding properties

3.1 Pursuit of higher J_c and optimization of processing conditions

The magnetic flux density that a multilayer sheet can shield is approximately proportional to $J_c \times d$ (thickness of superconductor)[12]. Accordingly, the shielded magnetic field ΔB_{sh} increases in proportion to J_c when d keeps at a fixed value. When ΔB_{sh} remains invariant, the larger J_c is, the smaller d becomes, which means that effective shielding is available with a thinner cylinder. An equation $\Delta B_{sh} = B_{ex} - B_{in}$ holds, where B_{ex} is an externally applied magnetic field and B_{in} is an internal magnetic field. Superconducting magnetic shielding entails refrigeration. It was also estimated that the shield would be exposed to a considerably high magnetic field as it was placed immediately close to the superconducting coil. Thus, higher J_c was considered necessary to improve the magnetic shielding properties from the outset of development.

Improvement of J_c depends on the microstructure inside the NbTi layers, especially the size and distribution density of microprecipitation in the α-Ti phase. The reason is described in Section 4 below. To optimize α-Ti precipitation, processing conditions had to be optimized. Intermediate heat treatment under conditions such as a total of three cold rollings at a cold reduction of 50%, a heat treatment temperature between 380 and 450°C, and a holding time of 2 to 5 hours was conducted repeatedly. Finally, 76% cold rolling was conducted to achieve a thickness of 0.75 mm (with the thickness of an NbTi layer being about 8 μm). **Fig. 4** shows the J_c values meas-ured with several applied magnetic fields for three different treatment conditions after the process above: (a) only cold rolling is applied, (b) heat treatment at a comparatively high temperature for a comparatively short period (400°C × 120 h) is applied, and (c) heat treatment at a comparatively low temperature for a comparatively long period (350°C × 672 h) is applied[13].

Measurement was made by the four-probes method. The applied magnetic field was normal to the current path, and parallel to the NbTi layers. J_c was determined by the electric field criterion of 1 μV/cm. The sample was dipped in liquid He and the temperature of the sample was 4.2 K. The characteristics of the multilayer material mentioned hereafter were all evaluated at the temperature of 4.2 K. J_c has anisotropy caused by rolling and the J_c with the current path normal to the rolling direction (C) is higher than the J_c with the current path parallel to the rolling direction (L) in each of the above conditions. The highest J_c was obtained with (c) of conditions (a) through (c) above in both the (L) and (C) cases entirely through the applied magnetic field from 2 to 8 T. It follows that aging heat treatment at a comparatively low temperature over a comparatively long period (c) was effective in achieving higher J_c. The J_c values measured in condition (c)-C were 1.58×10^9 A/m² (at 4 T), 0.91×10^9 A/m² (at 6 T), and 0.45×10^9 A/m² (at 8 T). The values indicated in brackets above indicate the applied magnetic field strength (T means tesla; 1 T = 10^4 G).

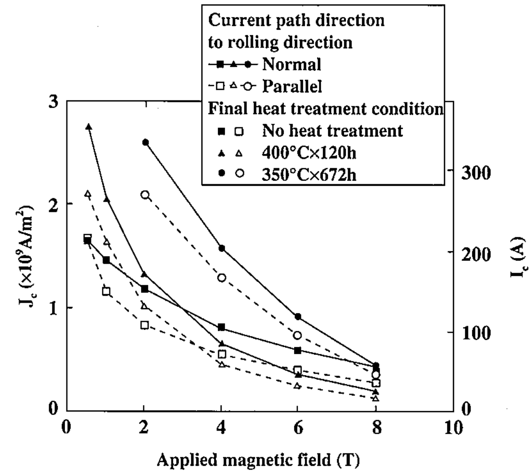


Fig. 4 Influence of applied magnetic field on critical current (I_c) and critical current density (J_c)

3.2 Shielding properties against DC magnetic field

Measurement was made on the conditions of the concentrically stacked cups, from number (N) one to five, which have the same multilayer structure as mentioned in Section 2, a thickness of 1 mm, an inner diameter of 20 through 40 mm and a length of 45mm. A sample consisting of the stacked cups was located at the center of the bore of a solenoid type superconducting coil, and a Hall probe was set on the axis at 4 mm above the innermost cup bottom.

Fig. 5 shows the results of the measurement[11]. Almost complete shielding of up to about 0.8 T is possible by a single cup, and stable magnetic shielding of up to about 3 T is possible with four cups. Especially, the externally applied magnetic field of up to 2.6 T was reduced to less than 10 G. With two cylinders with an inner diameter of 20 mm and 25 mm stacked, Hall probes were set at equal intervals on the axis and then the applied magnetic field B_{ex} was increased. **Fig. 6** shows the changes in shielding effect (S_{eff} [%] = $100 \times (B_{ex} - B_{in}) / B_{ex}$) against B_{ex} measured at each point[11]. Up to the middle

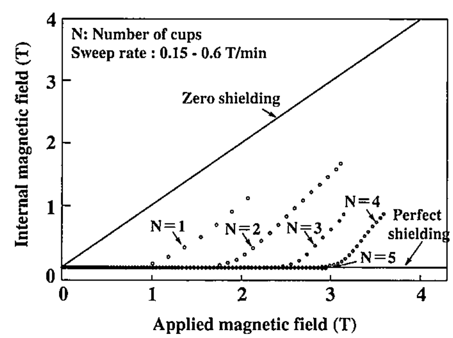


Fig. 5 Dependence of shielding properties of concentrically stacked cups on their stacked number N

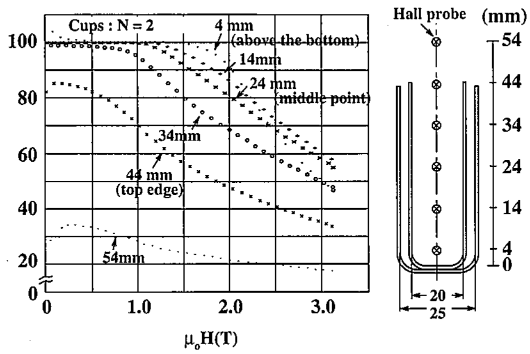


Fig. 6 Effect of axial distance from the bottom on shielding efficiency of two concentrically stacked cups

level from the bottom of the cylinder (24 mm above the bottom), the shielding effect was very high; almost 100% up to 1.0 T and higher than 90% up to 1.5 T. The effect is also satisfactorily high up to approximately three-quarters of the height (34 mm above the bottom): higher than 80% up to 1.5 T. It is noteworthy that the shielding effect exceeds 50% up to 1.5 T even at the top edge (44 mm above the bottom).

3.3 Homogenizing effect for magnetic field

A sheet of the same structure as the multilayer sheet in Section 3.2 above having a sheet thickness of 0.19 mm (an NbTi layer thickness of about 2 μm) was rolled up into a cylinder (referred to as a "Swiss Roll")[14]. The six layers of Swiss Roll was insulated from each other by paper. Then, the cylinder was coaxially inserted in the bore of a superconducting solenoid coil. **Fig. 7** shows the measured values of the axial component of the magnetic field at each point on the axis[14]. The horizontal axis and vertical axis respectively indicate the values of the distances from the center point on the axis and the normalized magnetic flux densities expressed regarding percentages of the magnetic field at the center of the coil as 100% when the Swiss Roll cylinder is not used. The 100% magnetic field strength at the center of the coil was 0.62 T. When the Swiss Roll cylinder was used, the magnetic field at the center of the axis was reduced by 25%, but the magnetically homogenous space was about 10 times larger[14]. In the future we will evaluate the limit level, J_c of the Swiss Roll cylinder, total thickness D (sheet thickness d × number of windings N), and the relationship between applied magnetic field B_{ex} and magnetic field homogenizing effect when using higher magnetic fields.

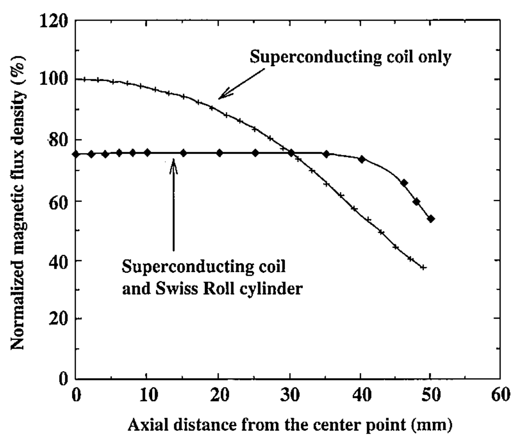


Fig. 7 Homogenizing effect for magnetic field by Swiss Roll cylinder

3.4 Shielding properties against AC magnetic field under a high DC magnetic field

One multilayer cylinder with the same structure as the multilayer sheet in Section 3.2 having a sheet thickness of 0.5 mm (an NbTi layer thickness of about 5 μm), an inner diameter of 15 mm, and a length of 90 mm was used for measurement. Two superconducting coils for AC and DC respectively were set concentrically at the center of the bore where the center point and axis were aligned. Then, a high DC magnetic field parallel to the axis was applied to the cylinder externally until Nb layers in the multilayer material lost their superconductivity. After that, an AC magnetic field parallel to the axis in a frequency range of 50 - 300 Hz was applied to the cylinder externally. To identify the shielding properties against magnetic field, the axial component of the DC magnetic field and AC magnetic field inside the cylinder sample were measured with a Hall probe and search coil arranged at the center of the axis.

Fig. 8 shows the results of the two cases of 50 Hz and 300 Hz[15]. The DC magnetic field applied externally was 1.53 T, while the DC magnetic field inside the cylinder was 1.10 T. This means that the cylinder sample provided a DC magnetic shielding effect, reducing 0.43 T at a sheet thickness of 0.5 mm. Since the lower critical magnetic field ($\mu_0 Hc_1$, where μ_0 is magnetic permeability in a vacuum) of Nb is 0.06 T and the upper critical magnetic field ($\mu_0 Hc_2$) is 0.4 T (at a temperature of 0 K)[1], all the Nb layers in the cylinder are supposed to be in the normal conducting condition and the shielding properties against AC magnetic field indicated in Fig. 8 would be attributed to the NbTi layers. However, in an AC magnetic field in this case, a certain level of shielding effect due to the eddy current generated in normal-conducting Cu and Nb layers may exist, too. A pure Cu (four-9 purity) cylinder of the same dimensions was prepared to measure the AC magnetic field shielding effect in liquid He (at a temperature of 4.2 K) in the same manner as above. The results were compared with those obtained from the superconducting cylinder.

The results showed that the Cu cylinder loses its AC magnetic shielding capacity at the frequency of 50 Hz and has AC magnetic shielding capacity of about 40% only at the frequency of 300 Hz, whereas the superconducting cylinder is not influenced by the frequency and a shielding effect of almost 100% is possible[15]. It should be noted that the plotted data is limited in AC applied magnetic field due to constraints on the power supply capacity, not due to an inherent limit in the shielding capacity of the superconducting cylinder.

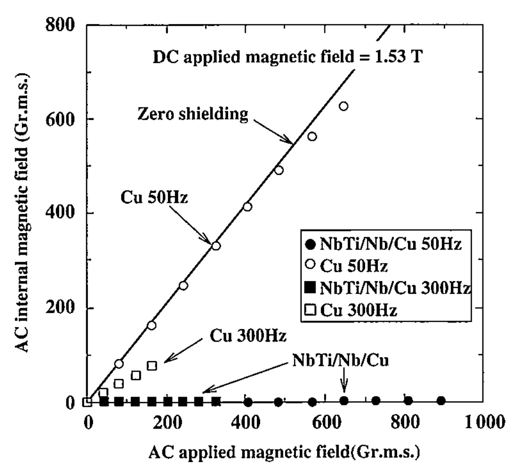


Fig. 8 Shielding properties against AC magnetic field of cylinder under a DC magnetic field bias

The limit levels of the AC applied magnetic field became low as the frequencies increased. In the future, we will examine the property limit levels of superconducting cylinders by using larger-capacity power supply units.

4. Internal microstructure, layer structure, and critical current density (J_c) of NbTi layers

4.1 Fluxoid and pinning point

When a magnetic field is applied to type 1 and type 2 superconductors, both types of superconductor remain in the Meissner state while the applied magnetic field is weak and the applied magnetic field penetrates a very thin layer near the surface only. However, in the case of a type 2 superconductor, applied magnetic field exceeding the lower critical magnetic field (μ_0Hc_1) enters the superconductor (referred to as "mixed state"). In the case of a type 1 superconductor, an applied magnetic field exceeding the critical magnetic field (μ_0Hc_1) does not enter the superconductor, resulting in a direct transition from a Meissner state to a normal conducting state. In this mixed state, the magnetic field in units of quantized magnetic flux (ϕ_0) is distributed uniformly, forming a triangular lattice, in the superconductor. The fluxoid lattice spacing a_f is 49 nm at 1 T and 22 nm at 5 T.

When current is applied to a superconductor, Lorentz force acts on the fluxoid. If this fluxoid moves in response to Lorentz force, a voltage is generated in the direction of current path and so electric resistance is generated, making it hard to maintain superconductivity. However, if the motion of the fluxoid is blocked, it becomes possible to maintain superconductivity and pass a large current. This effect is called the fluxoid pinning effect. A typical fluxoid pinning point is a normal-conducting precipitate. How does a normal-conducting precipitate pin a fluxoid? Energy does not change even when a fluxoid in a superconductor reaches a normal-conducting precipitate. However, the fluxoid in the normal-conducting precipitate needs to destroy the superconducting state to move into the superconducting section. As a result, extra energy is required and it becomes difficult for the fluxoid to leave the normal-conducting substance. In the case of NbTi, the fluxoid pinning point is Ti precipitate (α-Ti).

4.2 Pinning point and J_c value

Fig. 9 shows the TEM image of the cross-section in the L direction of the NbTi layer in an NbTi/Nb/Cu superconducting multilayer sheet which underwent 350°C × 672 h aging heat treatment. There are two Ti precipitates of different sizes indicated by the arrows. One is a large precipitate having a thickness of about 100 nm and a length of about 200 nm in the grain boundary; the other is a fine precipitate having a thickness of several nm and a length of several tens of nm in the grain[16]. The volume fractions of these precipitates after aging heat treatment are about 8% and about 6% respectively[16].

Ideal pinning points mean that normal-conducting substances as large as the diameter of the core of fluxoid (about 11 nm) are scattered at a spacing equivalent to the distance between fluxoid lattices (20-50 nm). It is also known from calculations that larger precipitates of an order of magnitude greater size, slightly influence the J_c value of this NbTi/Nb/Cu superconducting multilayer sheet[16]. With these two types of pinning point available, a critical current density of a practical level, namely 1.1×10^9 A/m^2 (in C direction, the multilayer sheet is parallel to the applied magnetic field), is obtained at 5 T[16]. However, the density level is only one half to one third of the J_c value of standard practical superconducting multicore wire material. The J_c value would be improved if a lot of fine Ti precipitates were generated. However, larger precipitates start to be formed only through aging heat treatment of 350°C × 8 h, while fine precipitates are not generated without applying aging heat treatment of 350°C × 336 h[17].

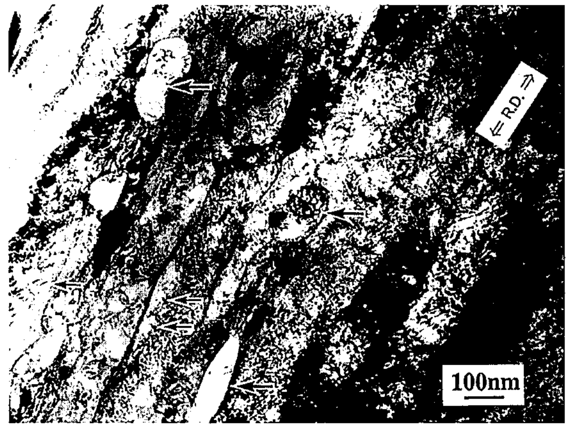


Fig. 9 Microstructure of NbTi/Nb/Cu superconducting multilayer sheet after aging heat treatment of 350°C × 672 h (Large Ti precipitates having a thickness of about 100 nm and a length of about 200 nm in the grain boundary and needle-like fine Ti precipitates having a thickness of several nm and a length of several tens of nm in the grain exist as fluxoid pinning points.)

4.3 Higher J_c through cold rolling after a long aging heat treatment

The presence of large Ti precipitates in this NbTi/Nb/Cu superconducting multilayer sheet cannot be avoided because a long aging heat treatment is indispensable in preparing this multilayer sheet. However, if the size of large Ti precipitates can be made smaller, it will be possible to improve the J_c value. We therefore examined the effect by thinning large Ti precipitates into foil by the rolling method. **Fig. 10** shows the inner microstructure of the cross-section in the L direction of the NbTi layer in the superconducting multilayer sheet which was processed by 50% cold rolling after aging of 350°C × 672 h. **Fig. 11** shows the dependency of the J_c value of the material which was processed by cold rolling after aging heat treatment on magnetic field as compared with the J_c value of the material which received aging heat treatment only. Fig. 10 clearly shows that large Ti precipitates are stretched thinly to a thickness of about 20 nm, which is a more appropriate size of precipitate to serve as a pinning point when

Fig. 10 Microstructure of NbTi/Nb/Cu superconducting multilayer sheet with higher J_c by 50% cold rolling after aging heat treatment (The thickness of large Ti precipitate is thinned to be about 20 nm as it is stretched by the rolling process.)

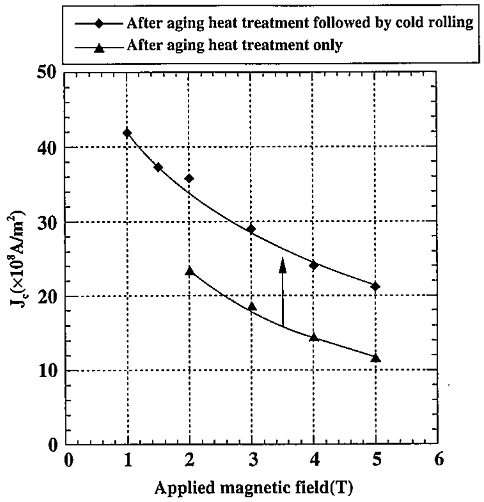


Fig. 11 Improved J_c value in the C direction of NbTi/Nb/Cu superconducting multilayer sheet after aging heat treatment followed by 50% cold rolling (with the magnetic field applied parallel to the multilayer sheet)

a magnetic field is applied parallel to the multilayer sheet[18].

As a result, when a magnetic field is applied parallel to the multilayer sheet, the J_c value was improved in the C direction in particular: approximately doubled to 2.3×10^9 A/m^2 from 1.1×10^9 A/m^2 (material after aging heat treatment) at 5 T. However, the improvement in the L direction was smaller compared to that in the C direction: improved by only 1.6 times to 1.1×10^9 A/m^2 from 0.7×10^9 A/m^2 (material after aging heat treatment)[18]. It is considered that cold rolling was applied such that the difference in hardness between the NbTi layer and Cu layer became large after aging heat treatment and the cross-sectional area of the NbTi layer was reduced as the layer was compressed in the rolling direction. It is necessary to improve the shape of the layer to improve further the J_c value in the L direction.

4.4 NbTi/Nb/Cu superconducting multilayer sheet containing Nb layers as artificial pinning centers

Since normal-conducting precipitate which is stretched thinly in the rolling direction serves as an effective pinning point (when applied magnetic field is parallel to the sheet), we prepared a superconducting multilayer sheet with normal-conducting layers artificially inserted, in other words, a superconducting multilayer sheet with Nb layers as artificial pinning centers, on an experimental basis. With this multilayer sheet, only the cold rolling process is required after bonding layers by the hot rolling process. Aging heat treatment is not necessary. The superconducting layers in this multilayer sheet consist of a number of Nb layers and NbTi layers, 580 Nb artificial pin layers and 551 NbTi layers. In order to roll the Nb layers and NbTi layers down to 40 nm or less, Cu-3Ni-0.6Si-0.2Zn alloy which has a similar hardness as NbTi and Nb was used as the matrix in place of Cu to prevent constriction. As a result, the J_c value (the applied magnetic field is parallel to the multilayer sheet) of the multilayer sheet having a thickness of 40 μm, an average thickness of Nb layer of 39 nm, and an average thickness of NbTi layer of 29 nm at 1 T increased three times to 1.5×10^{10} A/m^2 from the J_c value of the material with higher J_c (C direction) which received cold rolling after aging heat treatment[19].

5. Application examples of this superconducting multilayer material

Today, this superconducting multilayer material is supplied to national institutes, universities, private corporations, etc. both within and outside of Japan, and its performance has been proved in various applications. For example, DESY in Germany reported that they had successfully shielded a 1.1 T-DC applied magnetic field normal to the axis down to 0.01T within a stainless steel pipe by bonding two of the multilayer sheets having a thickness of 0.8 mm on and under the stainless steel pipe having a diameter of 50 mm like arcs, to evaluate the shielding performance of the material against the leakage field from a superconducting dipolemagnet in their particle accelerator line[20].

The University of California, Berkeley, reported that they had succeeded in almost completely shielding a 0.6 T-DC applied magnetic field by a small cylinder made of this multilayer sheet having a thickness of 1 mm to protect a highly-sensitive thermometer in a superconducting magnet[21].

The Brookhaven National Laboratory (equipped with particle accelerators) in the U.S.A. attached this multilayer sheet having a thickness of about 0.4 mm to the periphery of the superconducting inflector coil designed for allowing a muon beam to enter the storage ring for muons, in order to exclude the magnetic field to zero in the beam entry path without affecting the highly homogeneous magnetic field of about 1.5 T in the ring[22]. They reported that they were able to reduce the 25ppm displacement of homogeneous magnetic field measured without shielding to less than 1 ppm[23]. This experiment is considered to be epoch-making because it revealed very interesting data that could not be accounted for by the standard model of particle physics that has been the foundation of particle physics for 30 years, thus suggesting that a new theory superior to the conventional one needs to be developed[24]. The results of this experiment have been reported to largely depend on the magnetic shielding performance of the superconducting inflector making use of the superconducting magnetic shield[24].

Some papers have reported on the distribution of magnetic fields in both cases of shielding an externally applied magnetic field with a cylinder made of this multilayer sheet and magnetizing that cylinder, with the results of the analysis of superconducting current distribution along the axis direction under the above-mentioned conditions[25,26]. Another paper has reported that the researcher processed a multilayer sheet clad with Cu matrix and NbTi having a thickness of 0.2 mm like a mesh and measured the magnetic field going through the shield when an AC magnetic field of 100 Grms in a frequency range of 10 - 400 Hz was applied to a DC magnetic field having a very large magnetic field of 3 T. The paper stated that the field was reduced to 1 - 2 Grms with very little influence of changes in frequency[27].

6. Conclusions

This superconducting multilayer material has satisfactory magnetic shielding properties not only for tesla-level high DC magnetic fields as mentioned above but also for AC magnetic fields (fluctuating magnetic fields) under a high DC magnetic field bias of the same level, and also presents a unique homogenizing effect for magnetic field when placed in a superconducting coil. This superconducting multilayer material is being supplied to national institutes, universities, private corporations, etc. both within and outside of Japan, and an increasing number of studies on its basic properties and applicability are being conducted. The practicality of the material is being disclosed gradually. The processability, or workability, of the material is very high and the material can be processed by rolling or deep drawing, and so the material is suitable for preparing sheets and cylinders of various sizes and shapes. The material offers high potential for applications such as protecting parts vulnerable to strong magnetic fields in superconducting magnets; substantially reducing leaked magnetic fields or external fluctuating magnetic fields for securing precision measurement; reducing strong leaked magnetic fields from superconducting magnets by covering the periphery of such magnets; and achieving highly homogeneous magnetic fields by the simplified method.

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