Numerical Modelling of Twisted Stacked Tape Cables for Magnet Applications

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In view of HTS magnet applications, the concept of Twisted Stacked Tape Cable (TSTC) made of HTS coated conductors is very promising because of the easy manufacturing process and of the very high tape length usage. For the use of these cables in magnet applications, where the cables carry high current while subjected to the strong magnetic field generated by the rest of the magnet, the possibility of being able to calculate in detail current and field distributions is very welcome, particularly for evaluating the cable’s performance during the charge of the magnet. The numerical modeling of this kind of cable is particularly challenging because of the twisted geometry, which requires the use of a full 3-D transient model. In this paper, we use a 3-D finite element model to compute the current repartition among the tapes in a TSTC cable composed of several HTS coated conductor tapes. The utilized model is able to simulate not only the twisted geometry, but also the contact resistance of the electrical terminations used to inject the current. The latter can importantly influence the current repartition between the tapes, especially in short samples. The model is also able to take into account the angular dependence of the critical current on the local magnetic field, whose relative orientation with respect to the tape needs to be locally evaluated as a consequence of the twisted geometry. The performance of the cable in terms of effective critical current, AC losses and magnetization currents is discussed and compared to available experimental data.
Research of the influence of the gap between YBCO tapes on AC losses by extense Brandt model

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Abstract
We study the influence of mutual position of two tapes which are in parallel vertically and the size of the gaps between the tapes on AC losses. Since one tape is in the magnetic field which is produced by the other tape, the different gaps of the tapes can influence distribution of parallel and vertical component of the magnetic field, so do the AC losses. Firstly, a extense Brandt model is established to gain the current density in the tape. According to E-J power law, electric field can be calculated and AC losses can be calculated afterwards. By extense Brandt model, the changes of AC losses followed the changes of gaps will be obtained. At last we try to find a suitable gap to minimize AC losses. The research contributes to the design of the HTS current leads and cables in which the tapes are separated with different gaps. Moreover, we establish the experimental platform to measure AC losses, the experimental results are compared with theoretical results to verify the results of the theoretical model.

Keywords: AC losses; gaps; E-J power law; extense Brandt model

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Relationship between transport- and magnetization-$J_c$ in a BaHfO$_3$ doped PLD-Gd$_1$Ba$_2$Cu$_3$O$_{7.8}$ coated conductor

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Four probe transport method and magnetization method are both widely used to estimate critical current density, $J_c$, of coated conductors. However, we cannot compare $J_c$ values by these two methods directly because of the difference of electric field criterion. Usually, electric field criterion in the dc magnetization measurement is several orders smaller than that of transport measurement, therefore, we should extend electric field vs. current density ($E$-$J$) curves in such low electric field ranges. Power law $E$-$J$ relationship is widely used based on the transport measurements, however, the validity in such low electric fields is not yet clarified especially in-field measurements. In this study, we have investigated magnetic field, $B$, dependent $J_c$ in a BaHfO$_3$ doped PLD-Gd$_1$Ba$_2$Cu$_3$O$_{7.8}$ coated conductor by the four probe transport measurements and magnetization measurement using a SQUID magnetometer. In this sample, in-field $J_c$ has been increased significantly by the introduction of nano-rod structures as artificial pinning centers [1]. Relationship between the transport- and magnetization-$J_c$ is discussed based on the analysis taking into account $J_c$ distribution and flux creep within the framework of percolation transition model [2-4]. It has been shown that the $J_c$-$B$ characteristics obtained by the magnetization measurements can be described quantitatively based on the transport measurements [2] by use of Anderson-Kim type flux creep model together with the statistical $J_c$ distribution obtained from transport $E$-$J$ characteristics. Deviation from the power law $E$-$J$ characteristics, and magnetic field dependence of pinning potential will also be discussed.

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Characterization of In-plane Distribution of In-field Critical Current Density in RE-123 Coated Conductor Based on Reel-to-reel Scanning Hall-probe Microscopy

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We have characterized in-plane distribution of in-field critical current density in a coated conductor based on reel-to-reel scanning-Hall probe microscopy (RTR-SHPM). Local homogeneity in a coated conductor has become an important issue for its practical application because a local defect causes local burnout before being detected due to its very slow velocity in quench propagation. In fact, a manufacturer of a coated conductor has recently been attaching the information of local homogeneity, e.g., longitudinal distribution of local critical current evaluated by TAPESTAR™, together with the critical current tested by the four-probe transport method. However, such information is often taken near the self-field condition at 77 K; it has been reported that the correlation between the self-field properties at 77 K and the in-field ones at a lower temperature, where a practical application is to be operated, is not necessarily strong. On the other hand, it has also been reported that in-field properties at 77 K are well correlated with those at lower temperatures. This means that the local homogeneity of in-field properties is a key item which should be characterized as a quality control of a coated conductor. In this study, updating the RTR-SHPM system, we have succeeded in characterizing in-plane distribution of in-field critical current density in a long coated conductor. This will be a powerful technique for clarifying the significance and the positions of local defects in a coated conductor when it is introduced into a practical application.

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Measurements of Magnetization Losses in A Superconducting Coil under Changing External Magnetic Fields Spreading to Radial Direction

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Magnetization losses in a superconducting coil under changing external magnetic fields spreading to radial directions of the coil have been measured by new measuring method. This method measure Poynting’s vectors around a sample coil under changing external magnetic fields. Measuring sensors consist of one-turn pick-up coils for measuring local electric fields and pick-up coil for measuring local magnetic fields. These measuring sensors are arranged on the inner side, outer side, top, and bottom of the sample coil to cover the entire coil. This measuring method can measure the magnetization losses in the sample coil under external magnetic fields spreading to radial direction of the coil. The spreading magnetic field simulates magnetic profile at edges of an actual coil. A sample coil wound with Bi-2223 multifilamentary tape is exposed ac external magnetic fields spreading to radial direction of the coil in liquid nitrogen, and then measurement of magnetization of the sample coil have been carried out.
Characterization of Longitudinal Homogeneity of Local Critical Current in RE-123 Coated Conductor in High-field Condition Based on Reel-to-reel Magnetization Method

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We have developed a high-field measurement system for the characterization of longitudinal homogeneity of local critical current in a coated conductor based on a reel-to-reel magnetization method. Understanding of the local homogeneity in coated conductors has become an important issue for the design of practical applications because a local defect causes local burnout before being detected due to their very slow velocity in quench propagation. Recently, such information can be obtained by the TAPESTAR™ as a de facto standard method which gives longitudinal homogeneity of local critical current in a coated conductor near self-field condition at 77 K. However, considering magnet applications, the local homogeneity in high-field condition will be important for the determination of the design criteria of them. Furthermore, this will also be crucial for the evaluation of the spatial homogeneity in the introduction of artificial pinning center. In this study, we have characterized longitudinal homogeneity of local critical current in a coated conductor with the combination of a reel-to-reel conductor carrying system and a 5 T split pair magnet. The magnetization of the coated conductor was continuously measured by a multi-channel Hall-sensor, and then the corresponding longitudinal distribution of in-field critical current was estimated by considering the critical state model. We will show the first measurement results obtained by the system, e.g., longitudinal critical current distribution for several teslas at 77 K, although the system itself can deal with the angular dependence of magnetic field and 4 K condition.

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Angle Dependence of \( I_c \) with Strain in RCE-DR GdBCO Coated Conductor Tapes Under Low Magnetic Field

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The angular dependence of critical current, \( I_c \) with strain in RCE-DR GdBCO coated conductor (CC) tapes was determined using a newly constructed magnetic field application system. The characteristics of \( I_c \) with strain, magnetic field and angle of orientation to the tape surface, \( I_c (B, \varepsilon, \theta) \), can be evaluated simultaneously at lower magnetic field. A pair of Neodymium-based permanent magnet installed in parallel was used to apply an external magnetic field to the CC tape and the field intensity can be varied by adjusting the gap between them. The angle of orientation of external magnetic field with respect to the tape surface (a-b plane) was set by rotating the test rig fixture that holds the pair of permanent magnets. For most REBCO CC tapes, \( I_c \) is strongly dependent on the orientation angle of the CC tape sample in the applied magnetic field. This anisotropy becomes severe at higher magnetic fields. However, the strain sensitivity of \( I_c \) under low magnetic field of 0.5 T oriented \( B//c \)-axis is lesser compared with the case when it is oriented \( B//a-b \) plane. The strain sensitivity of \( I_c \) as a function of orientation angle was determined. \( I_c \) response on low magnetic field strength has been evaluated and the ratio of \( I_c \) at the condition of \( B//c \)-axis and \( B//a-b \) plane was measured to be \( \sim 2 \). As a result, the characteristic response of \( I_c \) with strain under magnetic field with varying orientation angle in the RCE-DR GdBCO CC tapes could be presented.

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A Study on the Degradation Characteristics of a Superconducting Wire according to an AC Electrical Breakdown

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The characteristics of a superconducting wire can be degraded by an electrical breakdown. In this paper, the degradation degree of three kinds of 2G superconducting wires after an AC electrical breakdown in saturated liquid nitrogen with 77K are measured. The three kinds of 2G superconducting wires are classified by the stabilizer metal such as stainless steel, copper, and brass. As a result, the electrical degradation degree of 2G superconducting wires after an AC electrical breakdown test is analyzed by measuring critical currents through a four probe method. Also, experiments on the degradation dependency of a critical current according to the repetition number of an AC electrical breakdown test are performed. Secondly, the degradation trend of an index n for three kinds of 2G superconducting wires after an AC electrical breakdown test is measured by plotting a VI curve. The degradation trend of an index n is analyzed by taking a scanning electron microscope (SEM) of a cross sectional view of 2G superconducting wires. It is found that the degradation degree of 2G superconducting wires are dependent on the hardness of a stabilizer. Furthermore, the dependency of an index n and the repetition number of AC electrical breakdown tests is also experimented and analyzed.
Numerical Simulation of Contactless Crack-Detection Method in HTS Film: Acceleration with Block LU Decomposition

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Recently, not only large-area high-temperature superconducting (HTS) films but also over 500 m long HTS films have been fabricated successfully. Since physical properties of HTS films are remarkably degraded by cracks, crack detection is essential in a production process of large-sized HTS films. For this reason, permanent-magnet method and inductive method have been applied to crack detection. However, both of them are extremely time-consuming. In order to drastically shorten the measurement time, Hattori et al. developed the scanning permanent-magnet (SPM) method [1]. In the SPM method, while a permanent magnet is moved along a film surface, an electromagnetic force acting on the film is measured. On the other hand, an evaluation of the shielding current density is indispensable for numerical simulations of the inductive method, the permanent-magnet method and the SPM method.

If the initial-boundary-value problem of the shielding current density is formulated by using the current-vector-potential method, integral forms of Faraday’s law on crack surfaces are also imposed as boundary conditions. After spatially discretized with the finite element method, the problem is transformed to the semi-explicit differential algebraic equation (DAE). Since the resulting equation is an index-1 DAE, the standard ordinary-differential-equation solver such as Runge-Kutta method can be applied to its numerical solution. However, it costs much CPU time to solve its initial-value problem. This is mainly because a linear system with a dense coefficient matrix must be solved several times at each time step.

In the present study, we develop a high-speed algorithm for solving the index-1 DAE on the basis of the block LU decomposition. By using the algorithm, we assess the applicability of the SPM method to crack identification in an HTS film.

Proposal of a critical current measurement scheme for 2,400 A class HTS wire using the pulse power supply

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The critical current is the maximum direct current that can be regarded as flowing without resistance in the superconductor. If operating current is exceeded the critical current, quench will occur that causes the transition of a superconductor from the superconducting state to the normal conducting state.

The four-terminal technique was used for the measurement of critical current in the international electrotechnical commission (IEC) – 61788. The applied magnetic field shall be parallel to the wide face and orthogonal to the wire axis of the HTS wire with rectangular cross-sections. The cooling temperature is 77 K, and the cryo-cooling method is impregnated with liquid nitrogen. If the critical current is near 2,000 A, the method cannot measure the accurate critical current because of the temperature increasing at HTS wire.

In this paper, the authors proposed a critical current measurement scheme using the pulse power supply to minimize the temperature changes at HTS wire.

The used wire at the critical current measurement experiment was SuNAM GdBCO 12 mm wire. Three cases with different parameters of temperature, magnetic field, and current density were tested. For the reliable measurement, a pulse power supply is selected considering the minimization of joule heating at copper terminal. Taking into account the above conditions, the power supply and cryostat were designed and fabricated, and the critical currents of several different cases were measured using the fabricated equipment.

The critical current of the case 1, 2, and 3 were 1,180 A, 1,220 A, and 2,340 A respectively. The measurement errors of the case 1 and 2 were under 1%. The measurement error verification of the case 3 is impossible because the critical current of the case 3 exceed the critical current data range of the wire. The proposed method will be applied to the high critical current of HTS wires.

Figure 1. The output current with bipolar pulse power supply.
EVALUATION OF TRANSVERSE TENSILE STRESS
CHARACTERISTICS OF GdBCO COATED CONDUCTORS

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Abstract

Recently, GdBCO coated conductor (CC) coils for high field magnets are investigated for practical use. GdBCO CC coils are subjected to longitudinal and transverse tensile stresses in their operation, so there is some research for mechanical properties of the GdBCO CCs in the recent years. Fujikura has also researched mechanical properties, for example, tensile or delamination strength, of the GdBCO CCs. In this report, we investigated pin-pull delamination test in Liquid nitrogen (LN2) to research mechanical delamination and critical current (Ic) degradation strength. We found out mechanical delamination strength is corresponding to Ic degradation strength. In addition, we experiment repeated transverse tensile stress on GdBCO CCs in LN2, most of the samples have more than 50 times at 50 MPa, which corresponds to single delamination strength, and there is no Ic degradation before mechanical delamination.
Microstructural Characterization of EuBa$_2$Cu$_3$O$_y$ coated conductor with BaHfO$_3$ nano-rods


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An EuBa$_2$Cu$_3$O$_y$ (EuBCO) layer with BaHfO$_3$ (BHO) nano-rods was deposited on a Hastelloy$^\text{TR}$ tape with a CeO$_2$/LaMnO$_3$/MgO/Y$_2$O$_3$/Gd-Zr-O buffer layer. We characterized the nanostructures of the coated conductors in the center part and edge parts of the Hastelloy$^\text{TR}$ tape along its width direction using scanning electron microscopy, transmission electron microscopy and a focused ion beam-scanning electron microscopy dual beam system. The EuBCO layer was mainly composed of $c$-axis oriented EuBCO grains with BHO nano-rods in both the center and edge regions. Some EuBCO grains whose $c$-axis was tilted away from the substrate normal were found in the EuBCO layers, which should prevent superconductive current. BHO nano-rods were formed in such the tilted EuBCO grains. The tilted EuBCO grains were formed on Cu-O or Cu-Ba-O grains with a few hundred nanometers. Since the volume ratio of Cu-O or Cu-Ba-O grains in the edge region of the EuBCO layer was higher than that in the center, the volume ration of tilted EuBCO grains in the edge region of the EuBCO layer was much larger than that in the center region. In order to achieve homogeneous superconductive current along the width direction of the Hastelloy$^\text{TR}$ tape, it is necessary to improve process conditions which could suppress such the Cu-O or Cu-Ba-O grains in the EuBCO layer.

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Flux Pinning Properties in YBa$_2$Cu$_3$O$_y$ Films with BaSnO$_3$ Nano-Rods and Spatially-Controlled Y$_2$O$_3$ Nano-Dots

(Kumamoto University)

The quasi-multilayered films consisting of YBa$_2$Cu$_3$O$_y$ layers with BaSnO$_3$ nano-rods and the pseudo layers of Y$_2$O$_3$ were fabricated using a multilayering process in a PLD method, with a view to investigating the hybrid pinning consisting of the 1D and 3D pinning centers. In particular, we focus on the influence of spatial distribution of Y$_2$O$_3$ nano-dots on the angular dependence of $J_c$. The prepared sample in this work is referred as Y($m$, $n$), where $m$ and $n$ denotes the number of laser pulses on the Y$_2$O$_3$ target and the total number of bilayers, respectively. In all the multilayered films, the total number of laser pulses on the Y$_2$O$_3$ was constant, i.e. 100 pulses. For lower temperature such as 65 K, a significant enhancement in $J_c$ was observed for all multilayered films for all magnetic field orientations compared to that of the pure YBCO film, except for $B \parallel ab$. The sample only with BaSnO$_3$ nano-rods has the highest $J_c$ for $B \parallel c$ in all applied magnetic fields. For lower magnetic fields, on the other hand, the $J_c$ in a series of Y($m$, $n$) samples are higher than that of the sample only with BaSnO$_3$, except for $B \parallel c$. This is attributed to the Y$_2$O$_3$ nano-dots working as 3D pinning centers, which trap the kinks of the flux lines depinned off the nano-rods for magnetic fields tilted off the $c$-axis. In addition, the $J_c$ for all multilayered films around $B \parallel ab$ is significant higher, which originates from the 2D pinning due to the pseudo layers of Y$_2$O$_3$ along the $ab$-plane.
Effect of Ho Addition On The Fabrication of MOD-GdBCO Films Using Fluorine-Free MOD Method

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It is essential to develop a low-cost fabrication process of high $T_c$ superconducting thin films with high $J_c$ performance for promoting the application of the films to coated conductors. The fluorine-free metal-organic deposition (MOD) method is a simple superconducting thin film fabrication process and suitable for the mass production. Doping of various elements to MOD-REBCO films; such as Zr or Sn, has been applied to enhance the $J_c$-$B$ properties. Furthermore, rare-earth oxides are known to be one of the candidates for artificial pinning centers in Pulsed Laser deposition (PLD)-REBCO films. However, there are few reports on the doping of RE elements to MOD-REBCO films.

In the present paper, we investigated the effect of Ho addition on the fabrication of GdBa$_2$Cu$_3$O$_y$ (GdBCO) superconducting thin films using a fluorine-free MOD method. Coating solutions for GdBCO thin films were prepared by using Gd, Ba and Cu 2-ethylhexanates solved in toluene. Ho was added to the GdBCO films by Ho 2-ethylhexanate solutions in concentrations of 1-10mol%. GdBCO precursor films were prepared on LaAlO$_3$(100) single-crystal substrates by coating the starting solutions and calcinating the coated films. Pure and Ho-doped GdBCO superconducting thin films were fabricated by firing the precursor films at 860°C and following oxygen anneal at 350°C. Both pure and Ho-doped GdBCO films showed a strong c-axis orientation from XRD measurements. The (00l) peak intensities of GdBCO films with Ho addition was strengthened with comparison to those of pure GdBCO films. Moreover, Ho-doped GdBCO films showed relatively flat surfaces with higher porosity than the pure films. The effects of Ho-doping on the superconducting properties and microstructures will be discussed in the paper.
Influence of Seed Layers on Growth of BaHfO$_3$ doped SmBa$_2$Cu$_3$O$_y$ tapes

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Developments of superconducting coated conductors have been carried out. The critical current density needs to be improved in high magnetic fields in order to apply for superconducting coils. A seed layer technique in the REBCO film deposition through a pulsed laser deposition (PLD) method enables to expand the appropriate growth temperature. Thus, it can control density and diameter of BMO nanorods in a wide range of the growth temperature. So far, we fabricated BaHfO$_3$ (BHO) doped SmBa$_2$Cu$_3$O$_y$ (SmBCO) films by the seed layer technique and reported increasing superconducting properties [1]. BHO nanorods within BHO doped SmBCO films formed firework structures [2]. However, the growth mechanism of the nanorods does not be understood well. In this study, in order to elucidate an influence of the seed layers on the BHO nanorods formation, BHO doped SmBCO films were deposited on the seed layer at various temperatures by PLD method.

The seed layer technique consists of two steps as follows; seed layers with the thickness of 100 nm were deposited at $T_{s\text{seed}}$=810 °C, and then upper layers with the thickness of 250 nm were deposited on the seed layer at various temperatures ($T_{s\text{upper}}$). SmBCO seed layers were fabricated on IBAD tapes and are abbreviated to Sm + BHO-seed. The films were fabricated at $T_{s\text{upper}}$=810 °C and 900 °C and the samples are abbreviated to BHO-810 and BHO-900, respectively. The volume fraction of the BHO within the seed layer and the upper layers was 1.4 vol. %.

Figure 1 shows magnetic field dependence of flux pinning force density, $F_p$. The magnetic field at maximum of $F_p$ ($B_{\text{max}}$) in the seed layer was almost identical to that of the BHO-810. Both films may have a similar BHO nanorods density, because the peak position would be decided by BHO nanorods density. On the contrary, the $B_{\text{max}}$ of the BHO-900 was lower than other films. These facts mean that the BHO density in the BHO-810 inherits from that of the seed layer, while the BHO-900 does not inherit. The BHO shape in the upper layer is influenced by the shape in the seed layer at low growth temperatures. However, high growth temperature gives a sufficient thermal energy for adatoms and the surface migration distance of the adatoms becomes larger. Thus, the BHO nanorods within the upper layer of the BHO-900 would grow independent of the BHO configuration in the seed layer.

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[1] Watanabe et al., Cryogenics Superconductivity Society of Japan, 2P-p09 (2013)

![Figure 1. Magnetic field dependence of flux pinning force density](image-url)
Low Temperature Fabrication of REBa$_2$Cu$_3$O$_y$ Epitaxial Films on SrTiO$_3$ (100) Substrate Prepared by Molten Hydroxide Method in 1-atm Air

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In order to apply coated conductors operated at boiling temperature of liquid nitrogen (77.3 K) to various fields, an improvement of the superconducting properties are required. In the case of REBa$_2$Cu$_3$O$_y$ (RE123; RE: rare earth elements) coated conductors, a biaxial orientation of RE123 crystals on substrate and the improvement of a critical current density ($J_c$) have been greatly conducted. However, these RE123 coated conductor needs a high growth temperature during film fabrication and cause degradation of superconducting properties due to impurity diffusion from metallic tape substrate. Moreover, for achievement of high critical current ($I_c$), a particularly technique for fabrication of more thick RE123 film is needed. Recently, we achieved the rapid fabrication of biaxial oriented RE123 epitaxial thick films on NdGaO$_3$ (001) single crystalline substrate fabricated by molten hydroxide method with low heating temperature of ~650°C in N$_2$ flow [1], although the NdGaO$_3$ (001) substrate causes high density cracks in RE123 film due to differential of thermal expansion between NdGaO$_3$ and RE123. In this investigation, in order to apply this novel technique, we fabricated the RE123 films using SrTiO$_3$ (100) substrate by molten hydroxide method in 1-atm air at low heating temperature (< 500°C).

The c-axis orientation of Nd123 films are shown in Figure 1. It is revealed that the low heating temperature (475°C) fabricated Nd123 films showed sharp and intense diffraction patterns of the RE123 phase. Moreover, we confirmed that these Nd123 films grown on SrTiO$_3$ (100) substrate with cube-on-cube ([100]Nd123//[100]SrTiO$_3$) orientation. From these results, we can conclude that the Nd123 film has biaxial alignment.

[1] S. Funaki et al., 26th International Symposium on Superconductivity 2013, FDP-7

Figure 1. XRD 2θ-θ pattern of Nd123 films as a function of heating temperature.
Fabrication of c-axis Oriented Epitaxial EuBa$_2$Cu$_3$O$_{7-\delta}$ and EuBa$_2$Cu$_4$O$_8$ Films on SrTiO$_3$ (100) Substrate by Molten Hydroxide Method at 450°C

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We have reported the fabrications of REBa$_2$Cu$_3$O$_{6.6}$ (RE124) films around 650°C in the air atmosphere$^{[1]}$, and of REBa$_2$Cu$_3$O$_{6.9}$ (RE123) films at low oxygen partial pressures at 550°C$^{[2]}$, by molten KOH. Molten KOH, however, reacts with or etches some substrates. Given this situation, we need more lowering temperature of fabrications and the answer is the molten eutectic NaOH-KOH method that can prepare RE123 at 450°C$^{[3]}$. In this paper, we study the effect of the eutectic NaOH-KOH on the molten hydroxide method and we try to deposit Eu123 and Eu124 on SrTiO$_3$ (STO) substrates.

Eu$_2$O$_3$, BaCO$_3$, BaO$_2$ and CuO were used as starting raw materials, whose the molar ratio was Eu:Ba:Cu = 1:2:4. KOH or NaOH-KOH (51.5:48.5; eutectic composition) was used as flux and weighed 200 wt% to the raw materials. The flux was melted in an alumina crucible at 700°C to remove water. The raw materials and STO (100) were put into the melt at 425-600°C and kept for 12 hours. After samples have been extracted from the flux by water and ethanol, synthesis phases and $T_c$’s was identified by X-ray diffraction and SQUID, respectively.

Fig. 1 shows the XRD 2$\theta$-$\theta$ patterns of the films fabricated using BaO$_2$ or BaCO$_3$ with eutectic NaOH-KOH at 450°C. In the case of using BaO$_2$, it is observed that there is no peaks diffracted from that of the Eu124 (00l) plane and they are c-axis oriented. Using BaCO$_3$, peaks of Eu123 (00l) and Eu124 (00l) can be seen. BaO$_2$ provides more oxygen ions in the melt than BaCO$_3$ (BaCO$_3$ releases CO$_2$ and becomes BaO). Accordingly, the difference of formed phases depending on the raw materials is coincident to the phase relation where RE124 is stable in high oxygen pressure than RE123$^{[4]}$. Fabrication temperatures were at least for 500-525°C with pure KOH.


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**Fig. 1.** XRD 2$\theta$-$\theta$ patterns of samples fabricated with (a) BaO$_2$ and (b) BaCO$_3$ by eutectic NaOH-KOH at 450°C
Flux Pinning Properties in GdBCO Coated Conductors Containing Columnar Defects with Splay Plane Parallel to Current Direction

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In order to reveal the effect of the crossing angle of splayed one-dimensional pinning centers on the angular dependence of $J_c$ properties, the heavy-ion irradiation was performed to introduce columnar defects crossing at $\pm \theta_i$ relative to the $c$-axis into the GdBCO coated conductors (Fujikura Ltd.), where the crossed plane of splayed one-dimensional pinning centers is parallel to the current direction. For the sample containing columnar defects crossing at $\pm 15^\circ$ relative to the $c$-axis, a single and sharp peak around $B//c$ was observed in the angular dependence of $J_c$. When the crossing angle was extended to $\pm 45^\circ$, a single peak becomes more broad around the $B//c$. For the sample containing the columnar defects crossing at $\pm 75^\circ$, on the other hand, not a peak but the improvement of overall $J_c$ was observed in the angular dependence of $J_c$. The splay plane would work as 2D pinning centers around $B//c$, while the correlated pinning centers consisting of crossing columnar defects weakens along the $c$-axis for the larger crossing angles such as $\pm 75^\circ$. For the magnetic field tilted off the $c$-axis, on the other hand, flux lines would be trapped by net-like pinning centers consisting of the crossing columnar defects, which leads to the broad peak of $J_c$ and the improvement of overall $J_c$.

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Influence of Spatial Distribution of 3D Pinning Centers on Superconducting Properties in BaMO$_3$(M=Zr, Sn, Hf) / YBa$_2$Cu$_3$O$_y$ Quasi-Multilayered Films

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In order to investigate the influence of spatial distribution of three-dimensional (3D) pinning centers, BaMO$_3$ (BMO, M = Zr, Sn, Hf) doped YBa$_2$Cu$_3$O$_y$ (YBCO) thin films were fabricated by a quasi-multilayering process using a pulsed laser deposition method. The prepared samples are referred as BMO($n$), where $n$ denotes the total number of BMO/YBCO bilayers. The $J_c$ values of BZrO(100) and BSnO(100) at $B = 1$ T and $T = 65$ K were improved in comparison with that of the pure YBCO sample. In addition, BSnO(100) shows the highest $J_c$ among all samples for all magnetic field directions. This is presumably because the particle-size of BSnO nanoparticles is the largest among BMO nanoparticles, that results in the effective pinning centers. On the other hand, the $J_c$ of BHfO(100) was lower than that of the pure YBCO sample. In the angular dependence of $J_c$ for BZrO($n$) samples, a broad peak centered at c-axis becomes gradually pronounced with increasing number of BMO/YBCO bilayers, i.e. with decreasing thickness of a YBCO layer. This result suggests that the positions of BaZrO nanoparticles within the films are more correlated in the c-axis direction with decreasing thickness of a YBCO layer.
An ion-beam assisted deposition (IBAD) is a promising method to obtain high performance REBCO (RE: Rare-earth, REBCO: REBa$_2$Cu$_3$O$_y$) coated conductors. We fabricated a long highly in-plane textured IBAD-MgO films on Ni based alloy substrates for REBCO coated conductor using the metal-organic deposition process including trifluoroacetates (TFA-MOD). In this work, the IBAD-MgO process was investigated for a developed architecture of RF sputtering CeO$_2$/RF sputtering LaMnO$_3$/IBAD-MgO/RF sputtering LaMnO$_3$/RF sputtering Al$_2$O$_3$/Hastelly to make long buffered metallic substrate with high properties. IBAD-MgO template films were deposited by RF sputtering of Mg metallic target and ion etched by the Ar ion beam. We optimized assist ion beam voltage, ion current and deposition temperature, time of the IBAD-MgO films. Fig.2 shows the $\Delta \phi$ values of the CeO$_2$ films verses film thickness of CeO$_2$ deposited on RF sputtering LaMnO$_3$/IBAD-MgO films. $\Delta \phi$ values were decreased with increase film thickness. Highly in-plane textured CeO$_2$ films deposited on the LaMnO$_3$ films. $\Delta \phi$ value of the 500 nm thick CeO$_2$ film was 4 deg. then we tried to deposit above 100 m long IBAD-MgO tapes. The above 100 m long IBAD-MgO films with about 4 deg. of $\Delta \phi_{\text{CeO}_2}$ in an XRD $\phi$ scan could be fabricated repeatedly.

In this presentation, we will report more details of our studies for IBAD MgO process.

Fig.1. Thickness dependence of $\Delta \phi$ for CeO$_2$ grown by RF sputtering on RF sputtering LaMnO$_3$/IBAD-MgO template films.
EFFECT OF OXYGEN ANNEALING TEMPERATURE ON THE IN-FIELD PROPERTIES OF TFA-MOD Y_{0.77}Gd_{0.23}Ba_{2}Cu_{3}O_{7-δ} COATED CONDUCTORS

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The trifluoroacetates-metal organic deposition (TFA-MOD) process is expected as a low-cost process to realize the power application using Y_{0.77}Gd_{0.23}Ba_{2}Cu_{3}O_{7-δ} (YGdBCO) coated conductors (CCs). TFA-MOD YGdBCO CCs have shown high self-field critical current density ($J_{c}^{s.f.}$) and in-field $J_{c}$ properties. For further enhancement of $J_{c}$ properties, it is necessary to improve for carrier concentration by optimizing oxygen annealing condition. However, the optimum oxygen annealing condition to get high in-field $J_{c}$ values in the TFA-MOD YGdBCO CCs is not clear.

In this work, we fabricated the TFA-MOD YGdBCO CCs with different oxygen annealing temperature ($T_{A}$) and oxygen annealing time ($t$), in order to elucidate the influence of carrier concentration to reflect oxygen content. We demonstrated that the CC at $T_{A} = 300 \, ^{\circ}C$ showed highest $J_{c}^{s.f.}$ values ( > 4.5 MA/cm² @ 77 K) and have the shortest c-axis length as well as the highest critical temperature ($T_{c}$) in this work. The optimum oxygen annealed CC has higher in-field $J_{c}$ compared with other CCs. At intermediate filed, the exponent $\alpha$ in the power law regime ($J_{c} \sim H^{\alpha}$) of the 300°C and 500°C CCs have $\alpha=0.63$ and $\alpha=0.73$, respectively. The 300°C CC shows higher $J_{c}$-B-θ property at 77 K and several fields compared with that of the 500°C CC, an improvement probably related to the enhancement of $J_{c}^{s.f.}$ by optimum oxygen annealing treatment in our TFA-MOD CCs.

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Magnetic Properties of the Stack of HTSC Tapes in a Wide Temperature Range

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The magnetization of HTSC stacks were measured in the temperature range T=4-80 K and dc magnetic fields up to 8 T. A single 10 mm by 10 mm square samples were cut from commercial (RE)BCO tape 10 mm wide and then stacked together. The number of layers in the stacks was varied from n=5 to n=250. Magnetization was measured by means of Hall probe which was placed directly on the stacks surface. The dependencies of remnant magnetization $B_{\text{rem}}$ on number of layers in the stacks at different temperature $B_{\text{rem}}(n)$ as well as on temperature $B_{\text{rem}}(T)$ at various $n$ were obtained. It was found that $B_{\text{rem}}(n)$ dependencies have a nonlinear character with a tendency to saturation for $n > 60$. The maximum remnant (trapped) field was found to be more than 2.5 T at T=4 K. The relaxation of trapped field was studied also and was determined that the rate of relaxation processes tends to decrease with the increase in a number of tapes in the stack. The correlation between dependency $B_{\text{rem}}(n)$ and dependency of magnetic levitation force measured at T=77 K at zero field cooling were found.

![Graph showing dependencies of remnant magnetization on the number of layers n in the stacks at different temperature.](image)
The Hundreds Meter Long buffer Layers based on IBAD for Coated Conductor

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Abstract: Coated conductors based on the high temperature superconductors REBa2Cu3O7−δ (REBCO or RE123; RE = Y, Nd, Sm or other rare earths) are expected practical materials application at liquid nitrogen temperature. Ion Beam Assisted Deposition (IBAD) and Rolling Assisted Biaxial Texture (RABI תו) are two main techniques to realize RE123 films texture on flexible substrates. Buffer layers were important for coated conductor which served as the barrier against elements diffusion between the metallic substrate and the superconducting layer during the RE123 processing as well as transfer the texture from substrate to superconducting layers.

Coated Conductors structured such as YBCO_MOD / LaMnO3_MS / MgO_MS / MgO_IBAD / Y2O3 / Al2O3 / Hastelloy are developed. Here, the development of buffer layers is introduced. Specially, the LaMnO3 cap layers which deposited by magnetron sputtering technique with a LaMn alloy target are detailed investigated, including power, substrate temperature, atmosphere and the different reactive gases. Hundreds meter long buffers with the in-plane full width at half maximum (FWHM) about 6.5° and the roughness of RMS about 2 nm in a 10*10 um range for LaMnO3 cap layers are successful prepared, which are suitable for sequence RE123 deposition.

Key words: Coated Conductor; IBAD; Buffer Layer; LaMnO3, Magnetron Sputtering.

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Improvement of In-field $I_c$ Property of PLD-EuBCO Coated Conductors by Controlling Distribution of Artificial Pinning Centers of BMO

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RE$_3$Ba$_2$Cu$_3$O$_{7-\delta}$ (REBCO, RE = rare earth) high-temperature superconductors (HTS) show relatively higher critical current ($I_c$) values especially under magnetic fields than other HTS wires/tapes. Therefore, REBCO HTS coated conductors (CCs) are expected for many applications, which are operated under high magnetic fields such as MRI and medical accelerators. Introduction of artificial pinning centers (APCs) such as BaHfO$_3$ (BHO), BaZrO$_3$ (BZO) and BaSnO$_3$ (BSO) into an REBCO HTS layer can improve the in-field $I_c$ value in wide ranges of temperatures and magnetic fields [1]. Recently, it was found that a combination of EuBCO + BHO materials showed the extremely high in-field $I_c$ value, and a 93.7 m long EuBCO + 3.5 mol% BHO CC with 108 A/cm-w (77 K, 3 T) was successfully fabricated using the IBAD/PLD process [2], [3]. However, it is not enough to optimize the growth conditions such as the target compositions, temperature, $P_{O_2}$, etc.

In this work, we aimed at further improvement of the in-field $I_c$ value of EuBCO + BMO materials by optimizing the target compositions. The film compositions and $I_c$ properties were measured by ICP and the standard 4-probe method for EuBCO + BHO CCs (1.3 $\mu$m in thickness) derived from the targets with the different compositions. Self-field $I_c$ values at 77 K of EuBCO + BHO CCs with different BHO ratios to Eu, which were 2.5, 3.5, 5.0 and 7.5 mol%, were 349, 377, 446 and 246 A/cm, respectively. In the previous work, there was some correlation between the self-field $I_c$ value at 77 K and the in-field $I_{c,\min}$ value, which was defined as the minimum $I_c$ value in the $I_c$-B-$\theta$ profile. Therefore, the more suitable BHO ratio could be 5.0 mol% than 3.5 mol%.

In this presentation, we will show the results on the influences of BMO ratio to Eu in target to microstructure and superconducting properties (self-field $I_c$ and in-field one).

This work includes the results supported by Ministry of Economy, Trade and Industry (METI) as “Development of Fundamental Technologies for HTS Coils” and by the New Energy and Industrial Technology Development Organization (NEDO) as “Development of Materials & Power Application of Coated Conductors”.

INFLUENCE OF HEATING RATE IN TFA-MOD Y$_{0.77}$Gd$_{0.23}$Ba$_2$Cu$_3$O$_y$ COATED CONDUCTORS ON CRYSTALLINITY AND SUPERCONDUCTING PROPERTIES

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The Trifluoroacetates-Metal Organic Deposition (TFA-MOD) process is one of the attractive processes to produce long length and low cost coated conductors (CCs). However, high production rate in the conversion steps is necessary for lower cost of Reel-to-Reel (RTR) long length TFA-MOD CCs. The heating rate in the conversion steps is the key factor for high production rate for TFA-MOD CCs.

In this work, we fabricated TFA-MOD Y$_{0.77}$Gd$_{0.23}$Ba$_2$Cu$_3$O$_y$ (YGdBCO) CCs with different heating rates ($R_H$) in the conversion steps in order to investigate the influence these fabrication conditions on superconducting properties. We find that the CC at $R_H$=5 °C/min has high crystallinity, as well as high self-field critical current density ($J_{c,s.f.}$) (4.0 MA/cm$^2$) at 77 K. However, $R_H$=30 °C/min CC shows low $J_{c,s.f.}$ (2.5 MA/cm$^2$). From Transmission Electron Microscope images, the growth of the YGdBCO at $R_H$=30 °C/min is delayed due to Y$_2$Cu$_2$O$_5$, CuO and BaF$_2$ are unformed during heating step compared with $R_H$=5 °C/min CC. Therefore, we introduce interim annealing process to form Y$_2$Cu$_2$O$_5$, CuO and BaF$_2$ before growth of YGdBCO. The $J_{c,s.f.}$ of $R_H$=30 °C/min CC using interim annealing process shows 4.0 MA/cm$^2$ at 77 K, which is 1.6 times higher than that CC without interim annealing process. We consider that the interim annealing process is a potentially useful technique for RTR long length TFA-MOD CCs.

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Development of long REBCO coated conductors by PLD method with high production rate

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REBCO with BMO (BaMO\text{X} : M = Zr, Sn, Hf, etc.) coated conductors can be expected to apply to the industrial and commercial applications at high temperature in magnetic fields. Recently, we found that \( I_c \) and \( J_c \) values of EuBCO with BHO (BaHfO\text{3}) coated conductors at high temperatures in magnetic fields were superior to those of other combinations of REBCO and BMO for coated conductors in wide ranges of temperature and magnetic field.

REBCO layers containing rods of the BMO phase deposited comparatively at a low production rate, for example, up to 10 \( \mu \text{m/h} \) has high \( I_c \) and \( J_c \) at 77 K in both self-fields and magnetic fields. However, the \( I_c \) and \( J_c \) properties at 77 K in both self-fields and magnetic fields of the REBCO with BMO layers deposited at high production rate of more than ten times as fast as \( \mu \text{m/h} \) remarkably decrease. To realize the low production cost for REBCO with BMO coated conductors, improvement of the production rate with maintaining high superconducting properties is required.

We optimized growth conditions including deposition temperature, T-S distance, \( O_2 \) pressure, and composition of REBCO with BMO target etc. for long tape fabrication to realize higher production rate with high superconducting properties. As a result, we fabricated an EuBCO with BHO coated conductor by Reel-to-Reel PLD method at a high production rate of about 40 \( \mu \text{m/h} \), which revealed the high \( I_c \) value of 246 A/cm\text{-w} and the high \( J_c \) value of 4.9 MA/cm\text{2} at 77 K and self-fields. The details of other superconducting properties, especially, in-field performance of EuBCO with BHO coated conductors fabricated by the high production rate PLD method will be summarized and discussed.

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Development of Splice Joint Technique for Long 2G Coated Conductor Tapes Using Ultrasonic Welding

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The jointing of 2G coated conductor tapes which has a low joint resistance is essential in fabricating coils, magnets, and power devices which needs several kilometers in length. Although manufacturers of CC tapes can now produce at best 1 km in length with high critical current, $I_c$, it is still not sufficient to fabricate coil windings. Several studies have been reported about different joint techniques such as solder joint and diffusion joint. In this study, CC tapes were joined by a newly developed joint method which employs ultrasonic welding (UW) process. This UW joint method utilizes a localized high frequency mechanical vibration under certain applied pressure to produce solid state joining between lapped CC tapes. Good joint technique should have strong adhesion without $I_c$ degradation and low contact resistance at the joint region as well as it should be cost-effective and simple way of jointing. Also, electro-mechanical properties of jointed CC tapes should be evaluated because various kinds of stresses and strains are induced during fabrication and operation. In this study, Cu-surround GdBCCO CC tapes adopting stainless steel substrate were supplied as samples. The CC tapes were joined by both lap-joint and splice butt-joint with face-to-face configuration. The critical current $I_c$ and joint resistance $R_j$ of the jointed CC tapes were measured at 77 K. Double bending test was carried out to investigate the bending tolerance limit of UW jointed CC tapes. The results were compared with those of single CC tape and mechanical-controlled solder jointed CC tapes.

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Keywords: ultrasonic welding, coated conductor, critical current, joint resistance, electro-mechanical properties,
Superconducting Properties (Jc-B-θ) of the Superconducting Joint between 2G Wires in Various Temperatures

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The low temperature superconducting (LTS) coils are used in present NMR / MRI devices and liquid helium is used for their cooling. However, it is possible to reduce the operating costs by manufacturing the superconducting magnet which is consisted of the high temperature superconducting (HTS) coil using liquid nitrogen cooling. The superconducting magnets used for NMR/MRI devices are operated in the persistent mode. Then the long-time field stability is required, and this stability is largely depends on the quality of the joints between superconducting wires. So, the joint techniques between 2G wires are very important issue and many studies have been carried out. Recently, the K·JOINS, Inc. has developed successfully the high performance superconducting joints between 2G wires by partial melting diffusion and oxygenation annealing process. In this study, the critical current density properties as functions of the temperature, the magnetic field and the angle on the developed superconducting joint between 2G wires are measured and estimated experimentally. In addition, the self-magnetic field distribution by transport current and trapped field distribution by field cooling method were measured at liquid nitrogen temperature by the high resolution Hall-sensor in order to estimate the quality of superconducting joint. The measured and estimated characteristics of the superconducting joints between 2G wires with various conditions will be discussed.
Fabrication of high $J_c$ (Bi,Pb)$_{2223}$ thin films by PLD and post-annealing process

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$(\text{Bi,Pb})_{2223}$ exhibits high $T_c$ compared to REBa$_2$Cu$_3$O$_y$ superconductors. It has been found that introduction of Pb into Bi based superconductors promotes growth of the Bi2223 phase [1]. The superconducting properties of the Bi based superconductor degrade in magnetic fields. The improvement of superconducting properties in the magnetic fields should expand the application field. Therefore, We fabricated (Bi,Pb)$_{2223}$ epitaxial thin films which grain boundaries were small, because the improvement of $J_c$ is expected. In addition, it is expected to improve $J_c$ in magnetic fields by means of an introduction of artificial pinning centers (APCs).

We fabricated (Bi,Pb)$_{2223}$ thin films on SrTiO$_3$ (100) single crystalline substrates by PLD method using Nd:YAG pulsed laser. However, Pb did not remain in the deposited thin films because of the high vapor pressure of Pb and the crystallinity of the films was poor. Then, we introduced face-to-face annealing technique in which a surface of a film is covered with another film [2]. The face-to-face annealing prevents the re-evaporation of Bi from the thin films. Moreover, in order to introduce Pb into the thin films, the face-to-face samples were annealed in Bi and Pb vapor atmosphere by embedding the samples into (Bi,Pb)$_{2223}$ sintered bulk.

After the annealing for 20 h, introduction of Pb into the thin films was confirmed. The XRD pattern of the annealed film contains strong 00l peaks of Bi2223. It indicates that the main phase of the film is Bi2223 and the annealed (Bi,Pb)$_{2223}$ film had $T_c = 101.2$ K. $J_c$ values in self magnetic field were 0.4 MA/cm$^2$ at 77 K Figure 1 shows the $J_c$ of (Bi,Pb)$_{2223}$ thin films at 77 K in magnetic fields applied parallel and perpendicular to the surface. We confirmed that $J_c$ of the fabricated (Bi,Pb)$_{2223}$ film in self magnetic field was improved compared with Bi2223/Ag tape[3]. However, $J_c$ in magnetic fields applied perpendicular to the surface rapidly degraded. Therefore, We will fabricate the (Bi,Pb)$_{2223}$ thin films including impurities. We expect that $J_c$ of (Bi,Pb)$_{2223}$ thin films in magnetic fields would be improved as introducing and controlling metal or metallic oxide.


Fig.1 $J_c$ of (Bi,Pb)$_{2223}$ thin films in magnetic fields applied parallel and perpendicular to the surface at 77 K.
AC Loss Analyses of Superconducting Power Transmission Cables Using Narrow BSCCO Tapes

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The reduction of AC loss in high-$T_c$ superconducting (HTS) power transmission cable is crucial for its practical use. The AC loss analyses of HTS cables comprised of coated conductors are advanced, and it has been reported that the loss is able to be reduced by using coated conductors with narrow width [1]. On the other hand, in HTS cable comprised of BSCCO tapes, it has not been cleared which the AC loss is reduced or not by using narrow tapes. The authors have developed 2D FEM numerical model to calculate AC loss in HTS cables on the assumption that the cross section of the superconductor in BSCCO tape is approximated to an ellipse or a rectangle. In the case of mono layer HTS cables, they were comprised of 13 tapes with 4 mm in width, 26 tapes with 2 mm in width and 52 tapes with 1 mm in width. The inner diameters of the cables are all the same. The $I_c$ values of all cables are 2,600 A. The results are shown in Figure 1. This figure indicates that the AC losses of all cables are almost equal to the theory of monoblock model. It is found that the loss is increased with an increase of the tape width at high normalized current values $I_t/I_c$, but the effect of a reduction of the loss by decreasing the tape width is small. The dependence of the loss on the number of the tapes is also studied for the cable comprised of the tape with 1 mm in width. The number of the tapes is decreased from 52 to 48, namely the gap between adjacent tapes is increased, but the losses are slightly increased because of the decrease of the cable’s $I_c$.


Figure 1. Comparison between the AC losses of 4-mm cables, 2-mm cables and 1-mm cables.
Large Critical Current Density in Ti-doped MgB$_2$ Wire Prepared by High Energy Milling

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MgB$_2$ bulks were successfully synthesized by high-energy ball milling of element Mg, B and Ti powders at ambient temperatures. The mixed powder was ball-milled for 0-10 h using a ball-to-powder mass ratio of 10 and sintered at 750 °C for 2 h. The phase and microstructure of MgB$_2$ were characterized by means of X-ray diffraction (XRD) and Scanning electron microscope (SEM). XRD results reveal the appearance of a small amount of MgO impurity, the relative percentage composition of MgO phase is gradually increased with prolonged the milling time. It proved that the sample milled 5 h has the best homogeneity in grain size. The milled 5 h powders were further processed to wires. The wire samples were fabricated by the in-situ powder in tube (PIT) method. Ball milling can cause a high reactivity of the precursor, which is beneficial to the MgB$_2$ formation. The investigation showed the high-energy ball milling is effective to obtain high density and fine grain size MgB$_2$ wire with high $J_c$ performance.
Synthesis of High Connectivity \textit{Ex-situ} MgB\textsubscript{2} Bulks by Short Time Self-Sintering

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In general, MgB\textsubscript{2} bulks prepared by the \textit{ex-situ} method have higher packing factor than the \textit{in-situ} bulks. However, intergranular coupling was much weaker due to limited contact area and presence of impurities at grain boundaries. In our previous study, \textit{ex-situ} MgB\textsubscript{2} bulks prepared by heating at \textasciitilde 900\textdegree{}C for \textasciitilde 100 h under ambient pressure showed evidence for self-sintering and enhancement of intergranular coupling [1,2]. On the other hand, because such long duration of sintering would cause generation of impurities by evaporation of Mg and reaction between sheath and core, shorter time sintering technique is essential to fabricate practical wires and tapes. Since controlling purity and grain size of MgB\textsubscript{2} powder is important for promotion of self-sintering reaction [3], MgB\textsubscript{2} powder with less MgO content and uniform grain size was prepared by \textit{in-situ} process in this study. \textit{Ex-situ} MgB\textsubscript{2} bulks were synthesized from the powder by sintering at 900\textdegree{}C for 1-24 h. XRD analyses confirmed that the \textit{ex-situ} MgB\textsubscript{2} samples are nearly single-phase with reduced amount of MgO. SEM images showed increased sintered MgB\textsubscript{2} grain boundary area and network structure which are indicative of promoted self-sintering. As a result normal-state resistivity largely decreased and connectivity was increased from \textasciitilde 20\% for the previous \textit{ex-situ} sample sintered for 96 h [2] to \textasciitilde 30\% for the present sample sintered for 1 h.


Doping level dependence of intergranular current density in polycrystalline Co-doped and P-doped Ba122 bulks

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The discovery of iron based superconductors [1] opened a new possibility for high-field applications [2]. Like cuprates, their intergranular supercurrent is suppressed by structural defects [3,4] and intrinsic weak-link [5,6]. To find effective ways for improving $J_c^{\text{global}}$, investigations on the current transport at natural grain boundaries using high purity polycrystals would be helpful. Here we performed comparative study using Ba(Fe,Co)$_2$As$_2$ and BaFe$_2$(As,P)$_2$ polycrystalline bulks prepared with systematically varied doping level to clarify the factors associated with high intergranular critical current density. Highly pure Ba, Fe, Co, As and P powders were mixed and ground by planetary ball-milling under Ar atmosphere. The milled powder was pressed into pellet, sealed in an evacuated quartz ampoule, and heated at 500-1100°C for 48-120 h. Powder XRD analyses revealed that 122 phase was obtained as main phase with high purity. Susceptibility measurement confirmed that optimally doped samples showed $T_c >$25 K. Remanent magnetization analysis showed that $J_c^{\text{global}}$ strongly depends on the doping level and its highest value exceeding 10 kA/cm$^2$ at 5 K was obtained by slightly over doping.

Effects of High-Pressure Annealing on Critical Current Densities in 122-type Iron-based Superconducting Wires

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Iron-based superconductors, such as LaFeAsO1-xFx [1], and Ba1-xKxFe2As2 (122-type) [2], are of great interest for applications due to their high upper critical fields and lower anisotropies [3]. The iron-based superconducting wires are one of the candidates of wires for superconducting magnet because of their higher critical current densities \(J_c\) under high magnetic fields. One of the most important issues related to their current carrying capability is how weak links between the grains in the wire are eliminated. In order to find a solution to this issue, we studied the effects of hydrostatic high pressure on \(J_c\) in 122 type iron-based superconducting wires. Although \(J_c\) was enhanced by HIP treatments in 122 wires, the quality of the wire core is still not optimized because of inhomogeneous carrier concentration and impurity phases [4,5]. In this talk, we will report the improvement of synthesis of polycrystalline 122 powders and the property of \(J_c\) in 122 type wires fabricated by hot isostatic pressing (HIP) technique under several pressures. First, polycrystalline \(AE_1_xK_xFe_2As_2\) (AE: Ba, Sr) samples were synthesized by solid state reaction. Intermediate compounds during the synthesis were mixed and ground by ball milling method to obtain homogeneous samples. Wires were fabricated by ex-situ powder-in-tube (PIT) method using silver and copper tubes. They were sintered in argon atmosphere under several pressures and temperatures. Using these wires we performed transport measurements, magnetization measurements, and magneto-optical imaging, and so on. The \(J_c\) in the HIP wire synthesized at 700 °C for 4h under 120 MPa argon atmosphere is several times larger than that in wires fabricated in a vacuum as shown in Fig. 1. It is caused by improvement of weak links between superconducting grains by high-pressure sintering. We will discuss the details of the fabrication of several wires and results of their physical properties measurements.


Figure 1. Magnetic field dependence of critical current density in (Ba,K)Fe2As2 HIP wire synthesized at 700 °C for 4h under 120 MPa argon atmosphere. \(J_c\) in the normal wire is former result in our group [6].
Fabrication of $K_xFe_{2-y}(Se_{1-z}S_z)_2$ Superconducting Tapes by a Chemical-Phase-Transformation PIT

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Abstract
The discovery of iron-based superconductors has activated studies on their applications as thin films, superconducting wires and tapes because of the high superconducting transition temperature ($T_c$) and the high upper critical field ($H_{c2}$). Among them, Alkali-intercalate iron selenide superconductors $A_xFe_{2-y}Se_2$ ($A = K, Cs, Rb, Tl/Rb$ and $Tl/K$) is one of the attractive materials due to their relatively high $T_c$ ($> 30$ K) and $H_{c2}$ ($> 50$ T).[1]

Furthermore, polycrystalline $A_xFe_{2-y}Se_2$ synthesized by liquid ammonia method shows a high $T_c$ of 30–46 K.

So far, iron-based superconducting wires and tapes have been fabricated based on an in-situ powder-in-tube (PIT) method or an ex-situ PIT method. However, these methods were not effective for $A_xFe_{2-y}Se_2$ wire. Recently, we reported a successful fabrication of FeSe and $FeTe_{0.4}Se_{0.6}$ superconducting wires and tapes by a novel PIT method based on chemical phase transformation of the wire core. [2], [3]

We have fabricated mono-core superconducting tapes of $K_xFe_{2-y}(Se_{1-z}S_z)_2$ using a process based on a chemical phase transformation from 112 type $KFe(Se_{1.2}S_{0.8})_2$ (non-superconducting) to 122 type $K_xFe_{2-y}(Se_{2-z}S_z)_2$ (superconducting) via an supply of Fe from the Fe sheath by annealing. The obtained superconducting tape showed superconductivity with a transition temperature of 29.1 K. The magnetic $J_c$ value of $1.6 \times 10^5$ A/cm$^2$ (at 4.2 K and self-field) was obtained for the sample annealed at 625 ºC for 5h followed by quenching. In this publication, we report the newest results of research.


Figure 1. Temperature dependence of zero-field-cooled (ZFC) and field cooled (FC) magnetization of $KFe(Se_{0.92}S_{0.08})_2$ tape core, $T_a = 600-675$ ºC 5h.
Development of practical Nb3Al superconducting strands for high-field application

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High-performance Nb3Al superconducting wire is a promising candidate for the high-field magnet application, like next-generation ITER, GHz-grade NMR, and LHC magnets and so on, since it has better strain-stress tolerance and in-field $J_c$ properties than Nb3Sn. In this paper, we reported our recent progress in developing practical multifilamentary Nb3Al superconducting wires, including the preparation of 18-filaments Jelly-roll Nb3Al precursor wires, Nb-Al diffusion heat-treatment and superconducting properties and microstructure of Nb3Al wires. The results suggest that for these Nb3Al wires, they are with critical transition temperature, $T_c$ of 12–15K, and well critical current density ($J_c$), up to 400–600 A/mm² at 4.2 K, 12 T. The key factors that affect superconducting properties of Nb3Al wires are also discussed.

Figure 1. Transport $J_c$ properties of low-diffusion Nb3Al superconducting wires at 4.2 K
2G HTS coated conductors using reactive co-evaporation with cyclic deposition and reaction (RCE-CDR) of HTS films onto simplified templates have been fabricated at Superconductor Technologies Inc. RCE-CDR is a low-cost, high-yield, scalable process for deposition of HTS films. Our simplified template structure consists first of a multi-layer metal oxide film deposited by solution deposition planarization (SDP) process onto Hastelloy substrates. Subsequently MgO is deposited via ion beam assisted deposition (IBAD). Multiple SDP chemistries have been screened and Design of Experiment (DOE) has been performed on IBAD process to optimize simplified template performance. Also silver and copper encapsulation on end-product has made progress. Through these improvements, hundreds of meters of templates are being fabricated. The 100m RCE-CDR is producing tens of meters of Coductus coated conductors carrying over 400A/cm of critical current. At the moment, RCE-CDR equipment scale-up is in progress to produce 1000m length HTS coated conductors. Along with the deposition chamber that will produce 1000m length, process control software is under development and this will incorporate real time process monitoring that enables fast adjustment to the process parameters during film growth for optimum HTS performance. Detailed data of Conductus wire will be presented at the conference.
Improvement of superconducting properties of GdBa$_2$Cu$_3$O$_{7-\delta}$ coated conductors by a post-annealing process

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We report the improved superconducting properties of GdBa$_2$Cu$_3$O$_{7-\delta}$ (GdBCO) coated conductors (CCs) by a post-annealing process. On the basis of the stability phase diagram of GdBCO, GdBCO CCs fabricated by a reactive co-evaporation deposition & reaction (RCE-DR) process were post-annealed at various high temperatures of $\sim$ 700°C in low oxygen pressures below 300 mTorr. In comparison with $T_c$ and $J_c$ of as-deposited sample, those of GdBCO CCs could be improved with the optimal post-annealing condition. It was found that the microstructure and superconducting properties of GdBCO CCs strongly depend on the post-annealing condition. In this presentation, details of the relationship among the post-annealing conditions, microstructure, and superconducting properties of GdBCO CCs are discussed.
Stability phase diagram of YBa$_2$Cu$_3$O$_{7-\delta}$ in low oxygen pressures (1 ≤ PO$_2$ ≤ 300 mTorr)

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We have investigated the phase stability of YBa$_2$Cu$_3$O$_{7-\delta}$ (YBCO) in low oxygen pressures (1 ≤ PO$_2$ ≤ 300 mTorr). In order to confirm the phase stability boundary and decomposition product of YBCO, Y-Ba-Cu-O amorphous precursor film deposited on LaAlO$_3$ (001) substrates at 200°C by pulsed laser deposition (PLD) were annealed at various high temperatures in low oxygen pressures. Experimental results commonly reveal that YBCO is decomposed into Y$_2$O$_3$ and YBa$_2$Cu$_2$O$_{6.5}$ and other phases in this low PO$_2$ region, which is quite different from the well-known peritectic decomposition of YBCO into Y$_2$BaCuO$_5$ + L in high oxygen partial pressures. In this presentation, details on phase stability and decomposition reaction of YBCO phase in low oxygen pressures will be discussed.
Study on The Field Properties and Pinning mechanism of YBCO Superconducting Film with Nb Doping

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YBCO/BYNO nano-composite was successfully fabricated by metal organic deposition method based on trifluoroacetate salts (TFA-MOD). The paper systematically studied the influence on the microstructure, surface quality and on the superconducting properties of the YBCO films with different content of Nb dopant. It is demonstrated that the microstructure of YBCO films had not an obvious impact for a Nb doping amount of less than 10mol.%, while the surface quality of YBCO is still improved. Although the critical transition temperature ($T_c$) of YBCO decreased slightly after Nb doping, it was kept as high as 90K for the present experiments. In addition, a significant enhancement of the critical current density ($J_c$) was observed for YBCO films with BYNO nanoparticles compared to those of pure YBCO films both in self-field and applied field. The epitaxial and random oriented BYNO nanoparticles coexisted in YBCO nanocomposites, which can be explained by the nucleation model. The size of the BYNO is between 20nm and 30nm, while the random fraction of BYNO was above 90%. The stacking fault parallel to the film and a serious lattice distortion of YBCO can be found around the BYNO nanoparticles, which could strengthen the nanostrain in the nanocomposite. As increasing the random fraction of BYNO, the nanostrain within nanocomposites was strengthened. According to that, the enhancement of field properties of BYNO resulted from the enhanced nanostrain. The present results can provide the basis for the enhancement of the in-field properties of YBCO nanocomposite.
Study on Fabrication of Ni5W long Tapes with CeO\textsubscript{2} Buffer layer by Reel-to-Reel Route

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10-meter-long home-made textured Ni5W long tape with a CeO\textsubscript{2} buffer layer has been prepared successfully by means of rolling assisted biaxially textured substrate (RABiTS) route followed by a chemical solution deposition (CSD) method in a reel-to-reel manner. Globally, the Ni5W substrate and CeO\textsubscript{2} film exhibit high homogeneity in terms of biaxial texture over the tape. The average values of full width at half maximum of in-plane and out-of-plane texture are 7.2° and 6.1° in Ni5W substrate, 7.6° and 6.1° in CeO\textsubscript{2} buffer layer respectively, all of those with a small standard deviation. On a micro level, the CeO\textsubscript{2} film epitaxially grows well on top of the Ni5W tape. A continuous, smooth and crack-free morphology was observed on the CeO\textsubscript{2} film and the fraction of low angle grain boundaries (≤10°) is about 98%. This process is a potential possibility for producing long-length textured CeO\textsubscript{2}/Ni5W tapes for coated conductors with a low cost.

![Figure 1. FWHM values of φ-scans (lower) and ω-scans (upper) of CeO\textsubscript{2} film and Ni5W tape](image-url)