WB1-1-INV

Progress in ultrafast transient liquid assisted growth of high current density superconducting films and coated conductors

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High current superconducting wires have been one of the most challenging achievements during all the HTS era which encompasses many materials science and engineering challenges. Coated conductors of $YBa_2Cu_3O_7$ (CC-YBCO) have emerged as the most attractive opportunity to reach unique performances at high an low temperatures, while reducing the cost/performance ratio continues to be a key objective for their marketability. Chemical solution deposition (CSD) is a very competitive cost-effective technique which has been used to obtain nanocomposite films and CCs, however their growth rates is rather small (0.5-1 nm/s). To address this challenge, we are developing a novel growth approach, entitled Transient Liquid Assisted Growth (TLAG), which is able to combine chemical solution deposition methodologies with ultrahigh growth rates of liquid-mediated approaches (100 nm/s), being compatible with nanocomposite growth and coated conductors. In this presentation, I will revise our recent progress in TLAG-CSD in terms of growth mechanisms, nucleation kinetics, and growth rate, determined by in-situ X-ray imaging (100 nm/frame) under synchrotron radiation. Critical current densities up of 5 MA/cm2 at 77K are already realized in thin films. I will present the new defects landscape and the role of preformed nanoparticles in the vortex pinning of TLAG-CSD nanocomposites. Finally, the approaches followed to grow thick coated conductors will be discussed.

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Keywords: YBCO films, liquid assited growth, chemical solution deposition

WB1-2

Recent results on in-field properties in nanoparticle-doped TFA-MOD $REBa_2Cu_3O_y$ Coated Conductors

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Nanostructural modifications, in particular incoherent nanoparticle additions, have been shown to have great success in improving superconducting material performance[1], such as $REBa_2Cu_3O_y$ (REBCO) superconducting films and iron pnictide films [2,3]. To be effective, the nanoparticle (NP) size has to be tuned, and the density needs to be higher with no degradation of the matrix crystallinity and critical temperature (T_c) for greater enhancement.

We show how it is possible to tune to obtain both small size and high density of NPs while maintaining the crystallinity of the REBCO matrix deposited by metal organic deposition. We get significant improvement of the in-field critical current density (J_c) over a broad temperature range by changing the nanoparticle material and by modulating the precursor chemistry. The enhancements are seen not only in J_c but also in the reduction of the effects of thermal fluctuations (flux creep) over broad ranges of magnetic field and temperature. Moreover, we developed our simple pinning model in the case of adding NPs, and this model is in good agreement with experimental results for both cuprate and pinictide films. Detailed microstructural and superconducting properties for nanocomposite REBCO CCs will be presented.

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Keywords: Critical Current Density, Flux Pinning, Nanoparticles

WB1-3

Strongly Enhanced Critical Current in thickened $BaHfO_3$-doped $YBa_2Cu_3O_y$ Coated Conductors prepared by Vapor-Liquid-Solid Growth Technique

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In order to apply $REBa_2Cu_3O_y$ coated conductors (CCs) , it is indispensable to increase deposition rate and critical current (I_c). Therefore, to achieve a high deposition rate, Vapor-Liquid-Solid (VLS) growth technique, which combines PLD and LPE methods, has been proposed, [1]. Using VLS growth technique, it is possible to fabricate thin films with 5.3 nm/sec in the deposition rate [2]. In order to increase superconducting properties in magnetic fields, it is necessary to introduce Artificial Pinning Centers (APCs) in films. However, there are few reports of introduction of APC using VLS growth technique. Recently, we fabricated $BaHfO_3$ (BHO)-doped $YBa_2Cu_3O_y$ (YBCO) CC by using the VLS growth technique in 26.0 nm/sec of deposition rate and 1.4 μm in the thickness, and we confirmed the BHO-doped YBCO CC was increased I_c compared with that of pure YBCO samples[3]. In this study, we fabricated thickened BHO-doped YBCO CCs (1.4 – 4.2 μm) and investigated thickness dependence of crystallinities and I_c.

The VLS growth technique consists of the following three steps. The first step is to fabricate 3vol% BHO-doped YBCO layer as a solid layer. The second step is to form a liquid layer consisting of Ba-Cu-O on the solid layer. The last step is to supply BHO-doped YBCO through the vapor phase on the liquid and solid layers.

Fig. 1 shows thickness dependence of *a*-axis oriented ratio and FWHM of YBCO 006. Using VLS growth technique, there are no *a*-axis oriented grans in the thickened CCs. Moreover, it was confirmed that the FWHM of the YBCO 006 reflection decreases with increasing the film thickness. Fig. 2 shows applied magnetic field dependence of I_c in thickened CCs with the thickness of (a) 1.4μm (b) 2.8 μm and (c) 4.2 μm. I_c increased from 23 to 123 A/cm-w (77 K, 1 T) and from 7 to 56 A/cm-w (77 K, 3 T), respectively. We will discuss the superconducting properties in magnetic field at various temperature and investigate shapes of BHO nanostructures introduced into thickened YBCO CCs using TEM.

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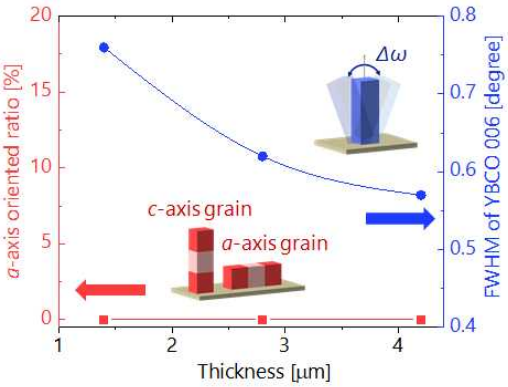

Fig. 1 Thickness dependence of *a*-axis oriented ratio and FWHM of YBCO 006

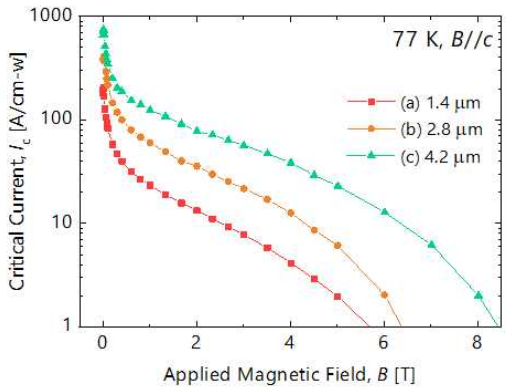

Fig. 2 Applied magnetic field dependence of I_c of (a) 1.4 μm (b) 2.8 μm (c) 4.2 μm thickened CCs.

Keywords: Vapor-Liquid-Solid Growth Technique, Thickened Film, High deposition rate, High magnetic field

WB1-4

Effectiveness of flux pinning by ion-beam induced defects at low temperatures

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Columnar defect tracks created by the passage of high-energy ions are well known to contribute strongly to flux pinning at 77K when the applied magnetic field is parallel to the tracks. A large and distinct peak can be observed in the angle dependence of the critical current (I_c) corresponding to the overlap of vortices and columnar defects. This is often offset though by a decrease of I_c at other angles due to reduced transition temperature T_c or reduced current percolation. When measured at lower temperatures, these peaks change significantly in shape and tend to broaden out approaching 20K. Coupled with being less sensitive to the reduced T_c this can lead to an enhancement of I_c over a wide angular range.

We have irradiated (Y,Dy)BCO coated conductor tapes from AMSC with 185 MeV Au ions or 50 MeV to 100 MeV Ag ions, and measured the magnetic anisotropy of I_c at temperatures from 20 K to 77 K and fields up to 8 T. We have seen that annealing at 200°C to 500°C following irradiation is generally beneficial, which we interpret as the restoration of oxygen order, but without the recrystallisation of the ion tracks.

The maximum entropy approach can be used to decompose the magnetic anisotropy into contributions from populations of pinning centres. We use this tool to track the evolution of peaks arising from ion irradiation over the available range of temperatures to understand how they combine with the background pinning landscape in different regimes.

Keywords: ion irradiation, flux pinning, critical currents, maximum entropy

WB2-1-INV

Recent progress in newly alloyed Nb_3Sn conductors

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The requirements for Nb_3Sn conductor for the realization of the Future Circular Collider (FCC) are very stringent. Particularly challenging is the target non-Cu J_c -(16T, 4.2K) of at least 1500 A/mm^2. Nowadays the best commercial Nb_3Sn strands can achieve only 1300 A/mm^2, demanding a significant improvement of the high-field J_c performance. To meet the FCC J_c target we developed new Nb-Ta-Zr, Nb-Ta-Hf and other alloys to introduce additional pinning centers while maintaining a high H_{Irr} in Nb_3Sn. Although the employment of SnO_2 can lead to the formation of ZrO_2 or HfO_2 precipitates, the best performances were obtained in the oxygen-free Hf-Ta-doped Nb_3Sn thanks to its very small grain size of less than 100 nm. This approach more than doubles the maximum of F_p and shifts its peak from 4.6 T, typical of Ta-doped wires, to 5.8 T on the Hf-Ta-doped conductor. This leads to a layer J_c(16T, 4.2K) of about 3710 A/mm^2, corresponding to a potential non-Cu J_c(16T, 4.2K) of 2230 A/mm^2. The microstructural analysis suggests a correlation between grain size of the alloys and the A15 phase. In particular the presence of Hf causes an increase in the recrystallization temperature of the alloy that then leads to the formation of small-grain A15. In this presentation we will discuss the sensitivity of H_{Irr} and F_p to heat treatment with respect to standard Ta/Ti-doped conductors and we will show the most recent results on multifilamentary wires and on the optimization of the dopant content.

Keywords: Nb3Sn, Critical current density, Pinning mechanisms, High Field

WB2-2-INV

Recent Progress of Nb_3Sn Wires in Furukawa

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Furukawa Electric Co., Ltd. (FEC) started the development of A15 superconductors such as Nb3Sn and V3Ga at early '70s and has focused on the development of multi-filamentary Nb3Sn wires through the bronze process. Since then, FEC has contributed to various fusion projects. such as MFTF-B and ITER. FEC also developed various type of Nb3Sn wires and cables collaborating with universities and national laboratories.

In this presentation, history and recent topic of Nb3Sn development at FEC are mentioned.

Keywords: Superconductor, wire, Nb3Sn, Bronze process

WB2-3-INV

Recent Progress of Nb_3Sn Wires in KSL/JASTEC

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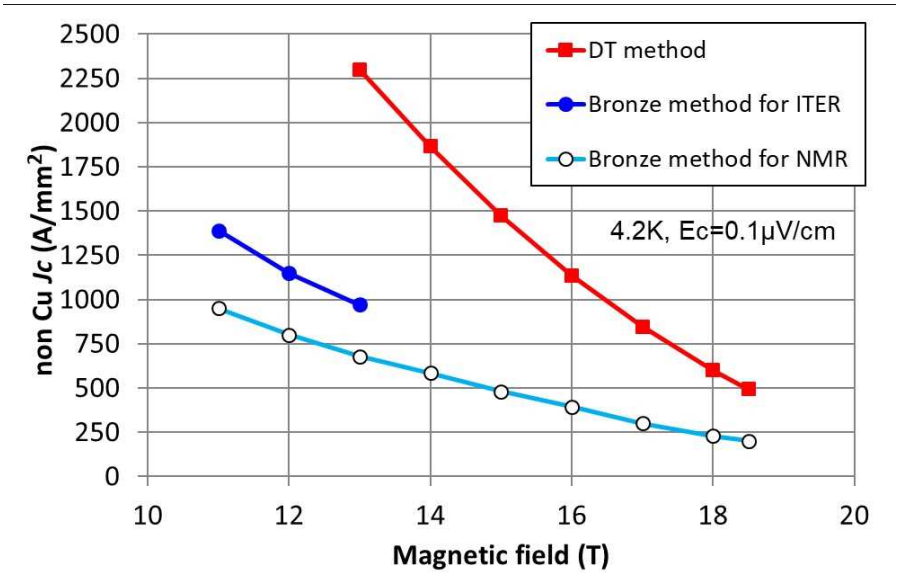
Kobe Steel Ltd. (KSL) has been doing researches of Nb_3Sn wire since the 1980s. Japan Superconductor Technology, Inc. (JASTEC), which belongs to Kobe Steel Group, has been manufacturing superconducting wires and magnets. In respect of the superconducting wires, JASTEC has high production capacity in bronze-processed Nb_3Sn wires and is one of the main supplier of Nb_3Sn strands used for ITER project. To increase *Jc*, we made the filament diameter finer and improve the heat treatment, and achieved very high performance of non-Cu *Jc* = 1200A / mm^2 at 12 T, 4.2 K by the bronze method.

Recently, according to the assumed specification of the Nb_3Sn for the accelerator magnets of the FCC (Future Circular Collider) planned by CERN (European Organization for Nuclear Research), it is required to achieve extremely high *Jc*, which is unprecedented, and high RRR (Residual Resistivity Ratio) and small effective filament diameter (d_{eff}).

We have developed high performance Nb_3Sn wire via DT (Distributed Tin) method, which is a type of internal Sn method with single barrier. So far, non-Cu *Jc* of 1,100 A/mm^2 at 16 T, 4.2 K has been achieved by reducing Sn diffusion length and optimizing Ti content. The d_{eff} of these samples were approximately 30 to 60 μm. The values of RRR were approximately 350, and RRR after 10% rolling assuming deformation of the cabling were 150 to 200, and no decrease in *Jc* was observed.

From these results, The DT method has very high potential as a candidate of Nb_3Sn wire for FCC. We will continue to improve *Jc* by further increasing Nb ratio and optimizing for the Sn diffusion distance, ternary additive elements and heat treatment, etc., for targeting the FCC's specification.



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Keywords: Superconducting wire, Nb3Sn, Bronze method, Distributed Tin method

WB2-4-INV

Recent research developments of iron-based superconducting wires and tapes

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Very high upper critical field and low anisotropy of iron-based superconductors (IBS) make them being particularly attractive for high-field applications, especially for the construction of nuclear magnetic resonance spectrometers, next-generation particle accelerators and ultra-high-field magnets. Conventional powder-in-tube method has been the most effective technique for fabricating IBS wires and tapes. Recently, significant progresses on the IBS wires have been made, in terms of both Jc enhancement and practical research. In this talk, the overview of the recent progress on Jc improvement and long wire fabrication will be provided. We also gives some advances relevant to practical applications, including scalable process optimization, composite sheaths, multifilamentary fabrication, mechanical properties and superconducting joints.

Keywords: iron-based superconductors, wire and tape, Jc

WB3-1-INV

HTS CroCo - a Strand for High Direct Current Applications

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High temperature superconductors (HTS) are discussed as energy-efficient solutions for applications needing high direct currents beyond 10 kA e.g. for large high-field magnets or busbar systems in industrial electrolysis plants. *REBCO* coated conductors are promising materials due to their excellent electrical performance at both, high fields and high temperatures. A number of high-current cable concepts based on REBCO tapes were developed such as the Roebel cable, co-axially wound tapes and several stacked-tape arrangements, among them the HTS CrossConductor (HTS CroCo), a stacked-tape conductor with high current density developed at KIT.

In this presentation, the conceptual design of high-current HTS cables based on HTS CroCo strands is discussed and the realization of a 35 kA demonstrator made from twelve HTS CroCo strands is presented. The demonstrator was tested successfully at $T = 77$ K, reaching the target performance 35 kA DC current at 77 K and even for a constant-current operation at 36 kA for more than 30 minutes limited by the copper connections, not the superconducting cable. Currents and voltages were measured over all twelve strands individually during the parallel operation in the cable. The measured data allow the experimental validation of the modeled current distribution calculated, based on the individual characterization of the twelve strands. The use of such cables for example in aluminum electrolysis will be discussed as a potential application.

WB3-3-INV

Development and Perspectives of HTS Cable-In-Conduit Conductor with Al-Slotted Core for Fusion Applications

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In the recent years, due to the increasing performances of the High Temperature Superconductor (HTS) REBCO-based conductors, i.e. *coated conductors*, the development of HTS based technology for extremely high field generation applications is emerging as one of the most favorable opportunities in nuclear fusion sector.

Pushed by this application perspective, new concepts of conductors incorporating HTS coated conductor tapes have been designed and implemented. Among them, a Cable-In-Conduit Conductor comprised of an Aluminum-slotted-core has been developed. In this cable the HTS tapes are stacked and inserted into helical ducts formed in an extruded Aluminum cylindrical core mostly studied in the 5-slots configuration (5 ´ 20 tapes – or 5 ´ 30, depending on tape thickness). The cable layout, designed aiming at the industrial feasibility of the manufacturing process, has shown promising electrical, thermo-hydraulic and mechanical properties assessed in several experimental studies of cable samples.

In this contribution, the status of the art of the Aluminum-slotted-core CIC conductor development will be presented. In particular, the manufacturing process, the electrical and mechanical behavior of the cable will be discussed based on the experimental results obtained in cable prototypes and numerical simulations with implemented cable FEA codes. On this basis, the most advanced concept of the cable with 6 slots and square jacket made of high strength Al – alloy has been developed. First results on the jacketing process and mechanical behavior will be provided showing how this solution is particularly suitable for fusion magnets. In this perspective, the road map of the cable development activities will be described. The layout and manufacturing details of the sample (sub-size conductor rated for 15 kA at 4.2 K and 12 T) for quench experiments to be performed in the next months at the SULTAN facility will be illustrated. In particular, preliminary experimental results of the electrical behavior and termination concept will be presented and the expected behavior of the cable described. These results supported by thermal-hydraulic/electric 1D multi-region conductor model implemented by PoliTo contributed to predict the quench propagation in HTS conductors.

WB3-4-INV

Development of Large-Current HTS Conductors for the Next-Generation Helical Fusion Experimental Device

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The Large Helical Device (LHD) has been successfully operated at National Institute for Fusion Science. Deuterium experiments, having achieved the ion temperature of 10 keV, proves the effective plasma confinement by the heliotron magnetic configuration. The design study of the LHD-type helical fusion reactor FFHR-d1 has also progressed. Presently, extension of the LHD project is proposed and discussed, with the main target showing the steady-state discharge capability under high heating power. In parallel, discussion for the post-LHD project has also been initiated, as one of the candidates is to build a new device employing a similar but more optimized heliotron magnetic configuration with magnetic field produced by the High-Temperature Superconducting (HTS) magnet system. A large-current capacity HTS conductor is required, and three candidates are now being developed: STARS, FAIR, and WISE. Firstly, the STARS conductor has been developed since 2005 to be applied to FFHR-d1. The REBCO tapes are simply stacked, imbedded into a copper stabilizer and stainless steel (SS) reinforcement jacket. A 3-m long 100-kA-class conductor sample, having a SS jacket sustained by bolts, was formerly fabricated and tested successfully. A bridge-type mechanical lap joint technique with low joint resistance has also been developed to make the “joint-winding” feasible. A 20-kA-class conductor is now being developed to meet the new target by selecting a suitable welding method for the SS jacket. Secondly, The FAIR conductor has a stack of REBCO tapes imbedded in a circular aluminum-alloy jacket. The stacked tapes are twisted together with the aluminum-alloy jacket, which is welded by Friction Stir Welding (FSW). A number of ~1-m long short samples, having different pitch length of twisting, are fabricated and tested, presently in liquid nitrogen. Thirdly, the WISE conductor is formed by inserting a stack of REBCO tapes into a flexible metal tube. Then, after the coil winding, the winding package is impregnated by filling a low-melting temperature metal. The advantage of this conductor is its flexibility during the winding process. Two prototype coil samples were fabricated and tested in liquid nitrogen. In this presentation, the design concepts and progresses of these large-current HTS conductors are reviewed.

Keywords: Large-current HTS conductor, LHD, helical / heliotron, fusion magnet

WB4-1-INV

Development and production of 2G HTS wires for moderate and strong magnetic field application at SuperOx

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Installation of the new manufacturing equipment at SuperOx Japan allowed for increasing HTS wire production capacity from 150 km/year (in terms of 4 mm wire) in 2018 to almost 400 km in 2020. At the same time, current demand for the standard 2G HTS wires based on GdBaCuO manufactured by SuperOx was almost satisfied, and development of new wires with improved Ic-B characteristics is necessary to expand the presence of SuperOx in the market.
Considering the prospective operating conditions of the future 2G HTS wires, we identified four target areas of interest for the development of the new HTS wires: 1) superconducting rotating machines (1-3T and 65-77K); 2) accelerator magnets and coils for levitating devices (3-5T, 30-40K), 3) superconducting magnets for fusion reactors (10-20T, 20K) and 4) high-filed NMR (30T, 4.2K).
To obtain such a new 2G HTS wire or a set of wires, which will possess considerably higher Je under the specified operating conditions, we employed the following development strategies:
- Optimizing the overall superconducting material stoichiometry;
- Variation of chemical composition by substitution into RE-site;
- Introduction of artificial pinning centers in the PLD process;
- Heavy ion irradiation of the HTS wires to create columnar defects;
- Fabrication of multilayered superconductor structures;

Extensive R&D yielded two prospective materials compositions for the production of wires with increased Je by the factor of two. Their Ic-B properties are optimized for medium and high magnetic field range application. Launch of the production of new 2G HTS wires was successfully accomplished in the 3rd quarter of 2019, and we expect to reach a benchmark of 300 km/year by the end of 2019 of the wires for the application in a high magnetic field.

Keywords: coated conductors, PLD, 2G HTS tapes, pinning

WB4-2-INV

Production and Development of REBCO (2G-HTS) Conductors

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The potential applications of Rare-Earth Barium Cupper Oxide (REBCO), Second-Generation High-Temperature Superconductors (2G-HTS), have been demonstrated in many projects for the last several years. This indicates the REBCO conductor is now being considered a robust and feasible solution for advanced devices and systems for a wide range of technologies. Efforts have focused on stabilizing and controlling processes to meet the requirements of high performance and large scale deployments.

This paper describes recent approaches to produce accomplished REBCO conductors with better performance and quality for industrial applications. Recent production improvements have delivered longer and more consistent conductor. Targeting in-field performance based on specific industry requirements and monitoring run to run consistency. Routine Ic-B-T-Θ performance and mechanical measurements benchmark process stability and control. Ongoing work to understand and requirements beyond 77K SF Ic to enhance processes for excellent performance and consistency across all critical demands conductor must meet.

Keywords: REBCO, HTS, SuperPower, Furukawa

WB4-3-INV

Present status of superconducting wire development in China: RE-123 CCs and related applications

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The activity of RE-123 Coated Conductor (CC) at Shanghai Superconductor Technology Co. Ltd (SST) and related applications will be presented.

SST coated conductor is progressing with focusing on the large market such as electric power applications and fusion such that 30 micron thin Hastelloy substrate tape was successfully produced in mass-production system. Furthermore, high Je at 4K and high fields was achieved at above 220kA/mm2 at 4K, 12T with Ic of 570A.

Recently we have many HTS projects in China including cable, FCL, accelerator, high field magnet and so on. Typical examples of these projects used SST tape will be introduced such as Shanghai Cable Project: 1.2km long REBCO cable installed in the center of Shanghai downtown.

Keywords: Coated Conductor, large scale production, high critical current, applications in China

WB4-4-INV

BMO Doped REBCO Coated Conductors with Uniform in-Field Performance and High Growth Rate by Hot-wall PLD Process

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Recent years we have participated in a 3 year program led by NEDO, MITI, to improve in-field transport performance and longitudinal uniformity of REBCO wires designed for 3-T class compact whole-body MRI magnet, without spoiling wire productivity. In this program, we concentrated on optimization of growth conditions for BMO-doped REBCO wires and found a high-growth rate deposition conditions of several 10s nm/sec, by using hot-wall type PLD process, which realized homogeneous crystalline growth conditions for REBCO by furnace-like substrate heating. In-field J_c properties of ~2-times bigger than non-doped ones were eventually obtained in low temperature range below 40 K. Those samples had a scattered short length BMO nano-rod structure, and a random pinning like scaling behavior was observed for the pinning forces in wide temperature range.

In-field J_c uniformity were characterized by Hall-probe magnetization measurement at 77K below 2.0T. Slight field dependent J_c enhancement and/or deviation were observed in several % length of measured samples, but quite good agreement observed for longitudinal J_c variations normalized by maximum J_c point up to 2.0 T. Furthermore, transport tests of 4-layered pancake coils have conducted by using a 34 meters long BMO-doped REBCO wire. The I-V characteristics of the coils agreed very well with numerical engineering estimations of angular dependent in-field J_c for BMO-doped REBCO wires.

Commercial shipment of the BMO-doped wire has started with production samples of 300-600m long and test samples of 1km long class also produced with good I_c uniformity comparable to non-doped REBCO wires. Mechanical reliability of those BMO-doped REBCO wires were also surveyed and the improvement od delamination strength were observed by total process refinement compared to past non-doped production wires. A part of this work is based on results obtained from a project subsidized by the New Energy and Industrial Technology Development Organization (NEDO).

Keywords: REBCO, Coated Conductors, Hot-Wall PLD

WB4-5-INV

Recent progress on the development of MgB_2 wires in Hitachi

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MgB_2 wires and coils have great potentials for helium free superconducting magnet. We have been concentrated on improving the longitudinal homogeneity of MgB_2 wire, and it was confirmed by making the magnet for klystron use by Wind & React method.
We will talk about how to bend the sintered MgB_2 wires without Ic degradation for React & Wind method. Three approaches can be thought for making the critical-bending-radius of MgB_2 wire smaller. First one is increasing the pre-compressive strain on MgB_2 filaments by raising heat treatment temperature. Second one is reducing tensile strain on MgB_2 filaments by moving the neutral axis of bending from the center of the wire. Last one is reducing tensile strain on MgB_2 filaments by arranging positions of MgB_2 filaments into center part of the wire. In this presentation, the results of improving the bending radius of the MgB_2 wire with the first and second approaches will be presented.

Keywords: MgB2 wire, Wind & React, React & Wind, bending radius

WB5-1-INV

Recent microstructural understanding to lead further J_c optimization of Bi-2223 tapes

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The Bi-2223 superconducting tape is the 1st generation high temperature superconductor (HTS). Due to its high T_c ~110 K, the devices made of Bi-2223 can be operated at the liquid nitrogen temperature 77 K. Especially the application of power electric utilities such as long distance power transmission cables have been investigated. Also this material is very attractive for high field magnets, since the irreversibility field (H_{irr}) becomes more than 20-30 T below 15-20 K. It has been more than a decade since Bi-2223 wires were industrialized. However, few times increase of the critical current density J_c is required in order to expand its practical applications and to make a substantial cost reduction of Bi-2223 wires. As a conductor, Bi-2223 is the most mature HTS, but in reality, there are so many unknown parameters in the manufacturing process because of the fact that Bi-2223 consists of 6 elements. In particular, the detailed structure of grains and grain boundaries and their correlations to J_c are still elusive. In recent years, we utilized high resolution Electron Backscatter Diffraction Orientation Imaging Microscope (EBSD-OIM) to visualize the grain structure in the industrial grade and proto type of Bi-2223 superconducting tapes. We found that the Bi-2223 grains are not stacked as the perfect brick wall model, but rather in the way that the c-axes are slightly tilted with a slight out-of-plane misorientation. The better out-of-plane grain alignment resulted in 24 % J_c increment. The in-plane grain orientations appear macroscopically random, but some of grains tend to form the domain structure in which the grain boundaries appear far less detrimental for J_c than previously thought. In this presentation, we will compare such microstructural features of Bi-2223 tapes and its sibling Bi-2212 round wires, and discuss the next challenge to further improve the J_c of Bi-2223 tapes.

WB5-2

Local-vs.-Global Current-Voltage Characteristics in HTS Tapes

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It is well established that a current-voltage (I-V) characteristics in HTS tape is generally rounded typically characterized by a power law model due to sever influence of thermal fluctuation and/or random pin distribution. It is crucial, therefore, to take into account such rounded I-V characteristics as a function of external magnetic field and temperature for a design of HTS based device. Generally, such I-V characteristics are measured by the four-probe method using a short piece sample or micro-bridge, then used as a design parameter of a coil or magnet, whereas an actual tape length in a device is in the scale of hundreds of meters or longer. However, the influence of a spatial variation on its I-V characteristics in a long length tape is not yet clear. In this study, we have investigated the relationship between a local I-V characteristics and a global one based on a measurement of reel-to-reel local Ic measurements and measurements on position dependent I-V characteristics of HTS tapes in both Bi-2223 and RE-123. Relationship among the power law I-V characteristics in local measurements, spatial variation of Ic and n-index, and the influence of flux pinning and thermal fluctuation will be clarified.

This work was supported by JSPS KAKENHI Grant Number 19H05617 and the New Energy and Industrial Technology Development Organization (NEDO).

WB5-3

Magnetic microscopy for NbTi-Bi2223 superconducting joints impregnated with different PbSn-based solders

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LTSs have been widely used in superconducting magnet application such as NMR spectroscopy and MRI. For a breakthrough in high magnetic field generation, HTSs are inevitable. However, to realize a practical high field magnet system, a superconducting joint between LTS and HTS is a key component to realize persistent mode operation. It was reported that a superconducting joint between NbTi wire and Bi2223 tape can be fabricated via the in-situ sheath-dissolution method using PbSn-based solder. Critical current (I_c) of the joint was measured by four probe method, which is dependent on the solder composition [1]. However, the influence of the local superconducting property and a limiting factor of the joint are not yet clear from such macroscopic measurement. Furthermore, it should be clarified the superconducting property at extremely low electric field criterion equivalent to the persistent mode operation. In this study, we have investigated spatial distribution of local critical current density (J_c) in the joint based on magnetic microscopy, to clarify the influence with different solder composition.

The magnetization current distribution of two superconducting joints impregnated with $Pb_{0.7}Sn_{0.3}$ and $(Pb_{0.7}Sn_{0.3})Bi_{0.4}$ was evaluated respectively. As a result, J_c around the NbTi shows high performance, while the J_c of Bi2223 is low in both samples. Difference between the two samples can be observed as follows. Firstly, the J_c of $Pb_{0.7}Sn_{0.3}$ solder is lower than that of $(Pb_{0.7}Sn_{0.3})Bi_{0.4}$ solder. Secondly, the magnetization current can flow across both edges of the Bi2223 impregnated with $(Pb_{0.7}Sn_{0.3})Bi_{0.4}$, while there is almost no current observed in the Bi2223 impregnated with $Pb_{0.7}Sn_{0.3}$. In addition, we measure the J_c distribution along the longitudinal direction of the Bi2223, showing low J_c and poor joint with the $Pb_{0.7}Sn_{0.3}$ solder similar to the in-plane distribution.

In summary, by visualizing the J_c distribution based on magnetic microscopy, we can conclude that the difference between two samples comes from the different superconducting property of the solders and the performance of Bi2223-solder joint. Furthermore, Bi2223 tape is the limiting factor of I_c in both samples.

This work was supported by the JST-MIRAI Program, JPMJMI17A2.

[1] R. Matsumoto et al., Appl. Phys. Express, 10, 093102 (2017).

WB5-4

Nanostructural Characterization of Jointed $GdBa_2Cu_3O_y$ Coated Conductors Using $YBa_2Cu_3O_y$ Intermediate Layer

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Recently a high temperature superconducting joint between $GdBa_2Cu_3O_y$ (GdBCO) coated conductors (CCs) was achieved using a GdBCO intermediate layer [1,2]. Using this joint technique and GdBCO coated conductors, a nuclear magnetic resonance (NMR) system was developed [3]. The NMR system was operated in a persistent-current mode in a magnetic field of 9.39 T at 4.2 K and detected NMR signals clearly. Instead of the GdBCO intermediate layer, an $YBa_2Cu_3O_y$ (YBCO) intermediate layer were applied to GdBCO jointed CCs to investigate the interface structures between CCs and the intermediate layer. An alcoholic solution of fluorine-free metallo-organic complexes with a Y:Ba:Cu molar ratio of 1:2:3 was spin-coated on one GdBCO CC. A spin-coated film was decomposed at 500℃ and microcrystallized at 800℃. The microcrystallized film and another GdBCO CC were pressed together and heated up to 800℃ for 20 min in an oxygen atmosphere to make superconducting joint named iGS® (intermediate Grown Superconducting) joint. We observed nanostructures of the GdBCO jointed CC using the YBCO intermediate layer by scanning electron microscopy (SEM) and (scanning) transmission electron microscopy ((S)TEM). Both of the GdBCO layers were connected to the YBCO intermediate layer. In addition, the *c*-axis of both the GdBCO layers and the YBCO grains composed of the intermediate layer were well aligned. Energy dispersive X-ray spectroscopy analysis indicated that the YBCO grains included Gd elements, which were considered to replace with Y elements in the YBCO. In addition, high angle annular dark-field image suggested that the distribution of the Gd elements in Y site in the intermediate layer was inhomogeneous. Those Gd elements were considered to be diffused from the GdBCO layers into the microcrystallized film (precursor of the intermediate layer) on the GdBCO layers during the iGS® joint process at 800℃. YBCO grains containing Gd in the intermediate layer would grow epitaxially on the GdBCO surfaces at the same time.
This work was supported by JST-Mirai Program Grant Number JPMJMI17A2, Japan.

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[2] K. Ohki et al., Supercond. Sci. Technol., **30** (2017) 115017.
[3] H. Maeda, Applied Superconductivity Conference (ASC), (2018) 4PL1B-01.

Keywords: HTS joint, iGS, TEM, STEM

WB5-5

Performance Evaluation of Practical REBCO CC Tapes for Superconducting Coils for Wind Power Application

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A Korea-type 10 MW-class large scale superconducting power generator with floating offshore wind power system which incorporates high-temperature superconducting (HTS) 2G coated conductor tapes for race-track coils are developing. Their operation conditions will be in a temperature range from 20 to 40 K and under a magnetic field of 2 T. Therefore, it is needed to investigate mechanical and electromechanical properties of commercially available practical REBCO CC tapes under the superconducting wind power application conditions. In this study, the electromechanical performance of differently processed REBCO CC tapes was evaluated at both test conditions of 77 K/self-field and 35 K/2 T using 4 mm wide and 12 mm wide REBCO CC tapes, respectvely. In addition, in the aspect of reliability assessment, the I_c degradation behaviors of 12-mm wide IBAD/RCE-DR Cu-stabilized GdBCO CC tapes using high-cycle fatigue test were investigated at 77K and at a stress ratio, R = 0.1. The correlation between the mechanical and electromechanical performances of practical REBCO CC tapes under specified test conditions were examined.

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Keywords: REBCO coated conductor, Electromechanical performance, Reliability, Superconducting coils for wind power

WB5-6

Progress in High-Speed Spin Testing of Superconducting Wire and Tapes for High-Field NMR Magnet Qualification

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This paper summarizes the status of a 3-year, NIH-funded research project to study the strength of high temperature superconductors under high circumferential hoop stress, in order to qualify these materials for high-field (> 1 GHz-class NMR magnets. The unique approach presented here is to spin test coils at high rotational speeds, approaching 100,000 rpm, in order to induce the necessary hoop stress. In this initial trial, short lengths of 2G YBCO thin-film tapes and reinforced Bi-2212 wires were mounted to a 75-mm diameter test rotor and spun. The results of this experiment, along with progress in building a second, higher speed rotor, are presented in this paper.

Keywords: superconductors, NMR, spin testing

WB6-1-INV

Towards Robust High Field Performance in Bulk HTS Magnets

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In 2014 we reported a record trapped field of 17.6T in an HTS bulk at 26K. While this was a pleasing achievement it did not pave the way immediately to practical operation at such high fields. Significant challenges remain including the fact that individual samples tend to only achieve high fields once, being damaged in the process and that most samples fail at fields much below the headline world record field.

In this talk I will report on progress that has been made in the Cambridge group in addressing these concerns. I will report on a new “Hybrid Stack” approach that has allowed us to achieve repeated magnetisation to 17.6T as well as progress in incorporating Silicon Carbide fibres into bulks to provide intrinsic reinforcement. Underlying this I will discuss our increased understanding of the behaviour of bulks under large magnetising forces.

Keywords: Critical Current, High Field, Bulk Superconductor

WB6-2-INV

Development of ultra small cryogen-free Superconducting Magnet for High-Resolution NMR

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In 2007, we reported observations of NMR signals of superconducting bulk magnets [1]. The first NMR signal was very broad and could not be used for analytical purposes. However, we achieved a magnetic field strength of 3T that could not be reached with a permanent magnet, found that the stability of the magnetic field was very high, and convinced that the bulk magnet could be used for NMR analysis if the inhomogeneity was solved. Using FEM, we determined the bulk magnet size to keep the magnet homogeneity from the commercial widebore (i.e. 89 mm inner diameter) NMR superconducting magnet to the superconducting bulk magnet. The concept of copying a homogeneous magnetic field from a superconducting magnet for NMR to a bulk magnet is based on a stack of several annular bulk superconductors and is placed on the NMR superconducting magnet using a magnetic field cooling method. By using this method and dealing with magnetic field inhomogeneities that occur during the magnetization process, the magnetic field homogeneity of bulk magnets has improved dramatically. In 2011, we reported the results of MRI [2], and in 2015 we reported a magnet that can observe chemical shifts by NMR [3]. We also found a way to compensate for the inhomogeneous that occurs when magnetizing by inserting HTS tape on the cylinder into bulk magnet[4]. Using these achievements, we integrated an RF probe, room temperature shim, and magnetic field lock system necessary for high-resolution NMR observation, and created a cryogen-free ultra-small superconducting NMR bulk magnet.

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Keywords: Bulk Superconductor, Superconducting Bulk Magnet, Bench-top NMR, Cryogen-free

WB6-3

Magnetic Flux Trapping and Flux Jumps in Pulsed Field Magnetizing Processes in REBCO and Mg-B Bulk Magnets

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Pulsed field magnetization PFM technique is expected to be a cheaper and easier way to utilize the HTS bulk materials as high field trapped magnets. As the heat generation due to the flux motion in the bulk magnets causes degradation of field trapping performances, the flux motions during PFM should be clarified in various modes of field applications. As a way among various field-feeding modes, the authors applied the various shapes and intensities of pulsed magnetic fields to the cryo-cooled RE123/Mg-B bulk magnets to watch the field invasion behaviors. In the PFM evolutional profiles, the authors classify the flux motion in three categories as “no flux flow (NFF)”, “fast flux flow (FFF)”, and “flux jump (FJ)”. To clarify the conditions which allow the flux jumps to happen, we may have a couple of approaches in our experimental procedures. One is the variation of evolutional profiles of pulsed field application, and the other should be a compositional or structural approach like a metallic inclusion arrangement to enhance the specific heat or heat draining structure. In the experiments, we observed the highest field trapping appeared at the upper end of NFF region, and FFF caused to FJ. This means the heat generation and its propagation paths should be attributed to flux trapping behaviors.

Keywords: bulk superconductor, pulsed-field magnetization, flux trapping, flux jump

WB6-4

Sm123 bulk superconductors composited by small-sized Sm211 particles formed by homogeneous nucleation catastrophe

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The refinement of RE_2BaCuO_5 (RE211) particles is of significant importance in preparing high performance $REBa_2Cu_3O_{7-\delta}$ (RE123) bulks by top-seeded melt-growth (TSMG). However, the pre-existing RE211 phase in the conventional precursor powder (CPP) inevitably results in its size-enlargement caused by coarsening and epitaxial growth. In our previous work, a novel modified precursor powder (MPP, Y_2O_3 and $Ba_2Cu_3O_5$) has been used to enhance the performance of $YBa_2Cu_3O_{7-\delta}$ bulks with Y211 nanoparticles. Here, we extended that new conception in the preparation of $SmBa_2Cu_3O_{7-\delta}$ bulks to reduce Sm211 size. Additionally, in order to suppress the Sm/Ba substitution, we replaced $Ba_2Cu_3O_5$ with $Ba_3Cu_4O_7$ to apply Ba-rich MPP (B-MPP). As a consequence, improved levitation force was achieved from the novel processed $SmBa_2Cu_3O_{7-\delta}$ bulk. Most importantly, this time and cost saving method is feasible to prepare other light rare-earth superconductor bulks (LRE123, LRE=Gd, Nd) with high performance.

Keywords: precursor, nanoparticles, SmBCO

WBP1-1

Improved performance of bulk MgB_2 superconductor produced via combination of in-situ and ex-situ method

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In this study, we propose a combination of in-situ method and ex-situ method, which are typical fabrication techniques in bulk MgB_2 superconductor system, to achieve high density as well as improve the critical current density (J_c). The bulk MgB_2 sample was synthesized with varying ex-situ powder (pre-synthesized powder) content such as 0, 10, 15, 20, 25 and 30wt% in conjunction with in-situ method followed by sintering at 775℃ for 3 hours in Ar atmosphere. As a result, it was observed that the filling rate, which represents the index of density, increased by 1% for every 5wt% increase of the ex-situ powder. Among all the samples, the 20wt% ex-situ added sample showed the highest J_c value of 321 kA / cm^2 at 20 K and self-field. Furthermore, it can be observed that all the ex-situ powder-added MgB_2 samples exhibit superiority in J_c values at the high magnetic field when compared with the sample fabricated by the in-situ method alone.

Keywords: in-situ, ex-situ, combination method, critical current density

WBP1-2

Superconducting Properties of Polycrystalline $Ba_{0.6}K_{0.4}Fe_2As_2$ Bulks Fabricated by a Spark Plasma Sintering Method

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Iron-based superconductors are expected to be applied in high magnetic fields, because it has a high superconducting transition temperature T_c and a high upper critical magnetic field H_{c2}. (Ba, K)Fe_2As_2 (T_c = 38 K for the optimal composition) is known to have a small electromagnetic anisotropy compared to the cuprate superconductors, therefore the polycrystalline samples, which were prepared by a powder-in tube [1] or a hot isostatic pressing (HIP) [2] methods, showed the relatively high critical current density. In this study, we attempted to produce the (Ba, K)Fe_2As_2 bulk by a spark plasma sintering (SPS) method and measured the superconducting properties.

Precursor powder of $Ba_{0.6}K_{0.4}Fe_2As_2$ was prepared by heating stoichiometric mixtures of pure Ba, K, Fe and As enclosed in the stainless steel tube under an atmosphere of pure gas argon. The obtained $Ba_{0.6}K_{0.4}Fe_2As_2$ powder was confirmed as the single phase by the powder X-ray diffraction method, and was sintered by the SPS method to produce a disk with a diameter of 10 mm and a thickness of 4 mm.

From the results of DC magnetic susceptibility, the onset of T_c was 35.0 K and the volume fraction of superconduction was 32.8 % at 5 K for the SPS-processed $Ba_{0.6}K_{0.4}Fe_2As_2$ bulks. A somewhat lower T_c suggested that the K substitution for the Ba-site might be incomplete. Thus, the optimization of the sample preparation such as the nominal composition of precursor powder and firing condition is now in progress.

[1] Z. Gao *et al.*, Supercond. Sci. Technol. **30** (2017) 095012.
[2] J D Weiss *et al.,* Supercond. Sci. Technol. **28** (2015) 112001.

Keywords: iron-based superconductors, Ba0.6K0.4Fe2As2, spark plasma sintering method

WBP1-3

Optimization of Sintering Conditions for Synthesizing Dense Magnesium Diboride Bulk Superconductors via Ex-Situ Spark Plasma Sintering Method

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Along with relatively high superconducting transition temperature (T_c), light weight, nontoxic, scalability, and simple synthesis procedures makes MgB_2 superconductors to be one of the promising candidates for accomplishing portable magnetic devices. Bulk superconductors developing for high field magnets, very high critical current density (J_c) values are required. Spark plasma sintering (SPS) is known as rapid synthesis method, suppressing the grain growth, and producing bulk products with high density into compact shapes. Therefore, the method is suitable to synthesize bulk MgB_2 [1, 2]. In this work, we have tried to synthesize bulk MgB_2 via SPS method with several synthesis conditions.
A series of samples were fabricated by varying the pulsed current intensity (350 A – 500 A). As the current intensity increased, MgB_2 decomposed mainly to MgB_4 and MgO. The impurity phase fraction was increased with raise in the pulse intensity while densification was not occurred at lower current and the 400 A was observed to be the best condition. The microstructural characterization reveals that the size of the MgB_2 grain was to be ~200 nm - 500 nm. Compared to the conventional solid-state sintering method, SPS samples own dense microstructures with remarkable grain connectivity. The obtained bulk MgB_2 materials were ~95 % dense as compared to a sintered product which possesses ~60%. The onset of T_c determined by SQUID magnetometry was ~38 K. The J_c of the sample fabricated by applying current of 400 A was exhibiting 220 kA/cm^2 at self-field and 20 K which is superior to the previous reports [1, 2]. Present results revealed that the SPS is a promising way to fabricate dense samples with improved grains connection and better densification of the bulk MgB_2 superconductors, which could be an important variant for magnetic applications. However, optimization of several parameters such as dwell time, applied pressure, doping, etc., can effectively enhance the flux pinning hence the J_c performance.

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[2] C. E. J. Dancer et al., Supercond. Sci. Technol. 22, 095003 (2009).

Keywords: MgB2, Spark plasma sintering, Critical current density, Dwell time

WBP1-4

Trapped Field Properties of Pulsed Field Magnetization of MgB_2 Bulk with Ti-doped

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Until now, some research institutes have magnetized MgB_2 by Field Cooled Magnetization (FCM) which is said to be the most efficient, but FCM requires a large device and power consumption is large and the time required for magnetization is long. Therefore, this time we used Pulsed Field Magnetization (PFM) to experiment that can magnetize in a short time and compact. In this research, trapped field characteristics were evaluated by pulse magnetization of MgB_2 prepared by HP method.

Samples used for PFM are shown in Table.1. The sample of this time was prepared by the HP method by changing Ti content. The sample was set on the cold stage and a hall sensor was attached to the surface center of the sample. After that, the inside of the chamber was evacuated and the sample was cooled by setting the freezer to 14K. The pulsed magnetic field was obtained by discharging a pulse current from a capacitor charged in a conductor coil cooled to 77 K with liquid nitrogen.

Fig. 1 shows trapped fields of each bulk. In this experiment, the highest trapped field was BT = 0.73 T of MH104b. Increasing the Ti content did not improve the captured magnetic field.

Table.1 Spec of Bulk

Sample Name	Diameter[mm]	Height[mm]	Mg : B : Ti
MH90-2,3,7	20	3.58	1 : 2 : 0
MH104b	20	3.67	0.975 : 2 : 0.025
MH113a	20	3.5	0.975 : 2 : 0.05
MH117	20	2.7	0.975 : 2 : 0.10

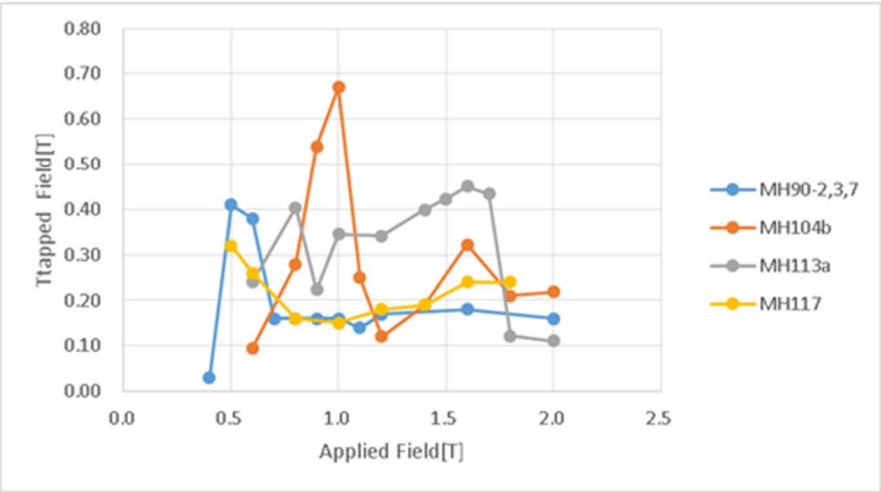

Figure.1 Trapped Field

Keywords: MgB2, Ti-doped, PFM

WBP1-5

Effects of SiC-doping on the trapped field properties of *in-situ* HIP-processed MgB_2 bulks

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MgB_2 bulk magnets have been strengthen by the densification, grain refining, and chemical doping. We found that the Ti-doped MgB_2 bulk fabricated by an *in-situ* hot isostatic pressing (HIP) method offered the high B_T of 3.6 T at 13 K [1]. C-doping is also well known to bring about the pronounced increase of both the critical current density J_c and the irreversibility field, H_{irr} [2]. In this paper, we report on the effects of SiC-doping on the trapped field properties of MgB_2 bulk. The $Mg(B_{1-x}(SiC)_x)_2$ (x=0-0.2) bulks were synthesized at 973-1173 K under gas-Ar pressure of 98 MPa by the *in-situ* HIP method, and then magnetized under 5 T by field-cooled magnetization. The B_T of 2.20 T at 20 K for the pristine bulk was increased to 2.25 T for the x=0.05 bulk and to 2.47 T for the x=0.1 bulk. However, further doping (x=0.2) deteriorated. On the other hand, the highest J_c and H_{irr} at 20 K were obtained for the x=0.05 bulk, and the J_c of x=0.1 bulk was somewhat smaller than that of the pristine bulk. We discuss an origin of the B_T-increase by SiC-doping in conjunction with the J_c properties, the connectivity, and the microstructure observation.

Acknowledgements:
This work was partly supported by JSPS KAKENHI Grant Numbers JP15K04718 and JP18K04920..

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[2] S. X. Dou *et al.*, Appl. Phys. Lett. Vol. 81 (2002) 3419.

Keywords: MgB2, trapped field

WBP1-6

Study on the thermal stability of the NdBCO film in inducing the growth of $REBa_2Cu_3O_x$/Ag superconductor bulks

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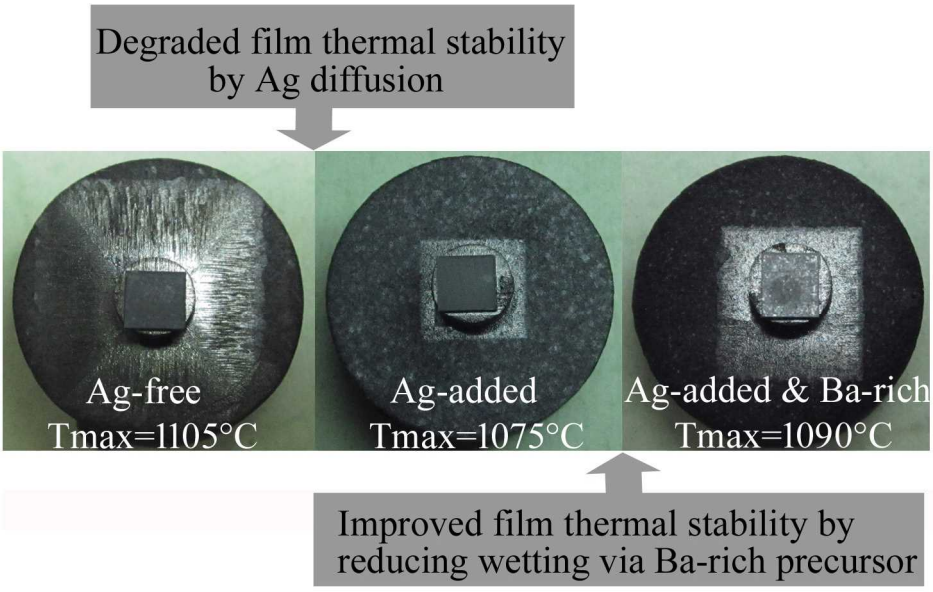
The NdBCO-film is a prominent seed in melt-growth of $REBa_2Cu_3O_x$ (REBCO, RE=rear earth element) cryomagnets because of its extremely high thermal stability, which, however evidently degraded, when Ag was added into NdBCO for improving its brittle nature, leading to fabrication failure. Here we clarified that film thermal stability is caused by high wettability of the Ag-added liquid, governed by precursor composition of REBCO/Ag. We developed a novel film seed/buffer-pellet/main-pellet construction to effectively strengthen film thermal stability via wetting modification by exploiting Ba-rich buffer-pellets, and succeeded in growing high superconductivity NdBCO/Ag bulks. This new conception is broadly applicable for producing all REBCO/Ag cryomagnets.



Graphical Absract: The top view of three kinds of NdBCO grown samples with procedures at their correspondingly tolerable maximum temperature(T_{max}).

Keywords: superconductor, thin film, wetting, thermal stability

WBP1-8

Effect of Carbon Nanotube doping on superconducting properties in Y-Ba-Cu-O Bulk Superconductors

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Melt-processed Y-Ba-Cu-O bulk superconductor can trap strong magnetic field at liquid nitrogen temperature and can act as a strong compact magnet, which is considered to be applicable for magnetic separation device, compact NMR and so on. In order to improve the performance of the field trapping Y-Ba-Cu-O bulk magnet, enhancement in critical current density J_c is required by embedding finely dispersed non-superconducting particles in the superconducting phase as effective pinning centres. Till now, an enormous number of works have been performed to increase in J_c by controlling the size and distribution of Y211 second phase. Recently, we have found that the addition of carbon nanotube (CNT) in the Y-Ba-Cu-O bulk superconductors is effective in increasing J_c. In this report, we have investigated the effects of two kinds of CNT addition on superconducting properties, such as single layer carbon nanotube (SWCNT) and multi-layered carbon nanotube (MWCNT). As a result, J_c value was improved when the SWCNT was employed rather than the case of MWCNT addition. From the microstructural observations, carbon-contained fine phases could be observed by SEM and compositional analyes by EPMA. We will present the distribution of the carbon contained phases and the affect to the superconducting properties (T^t, J_c, *etc*).

Keywords: carbon nanotube, melt-process, pinning centers, critical current density

WBP1-9

Study on superconducting welding method of Gd-Ba-Cu-O Bulk Superconductors for pulsed field magnetization

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We are investigating the effect of welding of Gd-Ba-Cu-O bulk superconductors on the trapped field properties obtained by pulsed field magnetization (PFM). RE-Ba-Cu-O bulk superconductors can trap a strong magnetic field below T_c, therefore, several applications like magnetic separation systems or motors using these strong compact magnets are being considered. The combination of bulk superconductor and the PFM method is one of the promising ways to design a simple superconducting bulk magnet device. However, in case of PFM, it is slightly difficult to trap a high magnetic field due to fast flux movement and heat generation during the PFM process. In order to overcome such a hurdle, we are studying welded bulk superconductors and the effect of an artificial superconducting grain boundary with different pinning and thermal properties compared to superconducting bulk body. There is a chance, by employing the artificial grain boundary by welding method, to enhance the performance of PFM processed magnets. In this paper, a Gd-Ba-Cu-O/Ag cut sample of 30 mm in diameter, taken from a single grain bulk, was split along the (110) plane then welded using Er-Ba-Cu-O/Ag solder. Trapped field distribution has been measured at 40 K after PFM with different applied fields. Finally, we discuss the potential of superconducting welding processes for the PFM.

Keywords: Bulk superconductor, welding process, pulsed field magnetization

WBP1-10

Magnetic Field Uniformity on Magnetic Pole of HTS Bulk Magnet System Attached Iron Plates with Holes

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The abstract is not released, but the poster presentation will be made.

WBP1-11

Pulsed field magnetization of GdBCO bulk using a ring-shaped soft-iron yoke

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We study to improve a trapped field of REBCO bulk excited by pulsed field magnetization (PFM). In PFM, there are some merits such as a magnetizing system is compact and inexpensive, and magnetizing time is short. It is very important to simplify a magnetizing process in order to accelerate a practical use of bulk magnet. Then, we focus on a soft-iron yoke which is used in order to expose the bulk to a large amount of magnetic flux for a long time. In our previous study, trapped field performance was investigated by varying a diameter of disk-shaped yoke. In this paper, we evaluate an influence of a shape of soft-iron yoke on magnetizing characteristic. A ring-shaped yoke with a 64 mm outer diameter, 20 mm inner diameter and 47 mm thick is newly fabricated. PFM experiment using a GdBCO bulk 60 mm in diameter and 20 mm thick is performed by varying an amplitude of applied field and temperature, and these results are compared with that of a disk-shaped yoke.

Keywords: GdBCO bulk, pulsed field magnetization, ring-shaped soft-iron yoke, trapped field

WBP2-1

The critical current properties of 19-filaments MgB_2 wires by an internal Mg diffusion process

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MgB_2 is considered as a promising candidate for engineering applications in the temperature range of 20-30 K due to its low cost of raw materials and strong intergrain connection. It was found that highly dense MgB_2 wires fabricated by internal Mg diffusion (IMD) have apparently higher current densities than the powder-in-tube (PIT) produced ones. Therefore, IMD also allows a higher engineering current density (J_e), which is one of the most important parameters for practical superconducting systems. We have fabricated 19-filaments MgB_2 wires using an internal Mg diffusion (IMD) process. The microstructure and transport performance of this 19-filaments IMD wire were investigated. For the IMD-processed MgB_2 wire fabricated by C-coated nano-sized B powder with 1.0 mm diameter, the critical current is about 546 A at 4.2 K and 4 T, which is far higher than that of the undoped sample. The best J_e is 6.9×10^4 A/cm^2 at 4.2 K and 4 T. The obtained results show that the C-doped IMD wires with excellent superconductivity and mechanical property can compete with the conventional PIT wires in practical application.

Keywords: Ceramics, Metalic composites, Microstructure, Functional

WBP2-2

Stability Evaluation of MgB_2 Wire Based on Conduction Cooling

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MgB_2 - superconductors have been drawing attention in electric power and magnet applications at temperatures around 20 K. It is also a highly promising alternative superconductor in development of cryogen-free MRI system, thermal stability problem must be addressed in such an application while related studies about MgB_2 magnets or even coils are quite limited. Behavior of MgB_2 wires must be understood before large systems are introduced. Herein, two crucial and fundamental parameters evaluating thermal stability of MgB_2 wire: Minimum Quench Energy (MQE) and Normal Zone Propagation Velocity (NZPV) were theoretically and experimentally evaluated under the condition of self-field at 20K. The experiment was based on cryocooler cooling. As a basis for the thermal stability evaluation, to begin with, critical current was measured by transform method. Output of heater mounted on the wire was used to trigger normal zone propagation in MQE and NZPV measurements.

Keywords: MgB2, Conduction cooling, Thermal stability , Quench

WBP2-3

Post-Annealing Effects of MgB_2 Thin Film Prepared on Stainless Steel Tape

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MgB_2 is an intermetallic superconductor with a high critical temperature (T_c) of 39 K, which leads to an operation temperature of approximately 20 K. We recently reported that high J_c of 6.4×10^5 A/cm^2 at 20 K and 5 T was achieved in the MgB_2 thin film prepared on Si single crystal substrate and then annealed at 550 °C [1]. For the development of practical superconducting wires, MgB_2 films should be deposited on metal tapes. In this study, we prepared MgB_2 thin films on stainless steel (SS304) tape with relatively high mechanical strength.

MgB_2 thin films were prepared on SS304 tapes by an electron beam evaporation technique and about 5 nm-thick Nb layers were deposited on the MgB_2 layers by using a coaxial vacuum arc evaporation gun. The Nb/MgB_2/SS304 specimens were then moved to a sputtering chamber and 1 μm-thick Nb layers were deposited on them for preventing Mg evaporation during the post-annealing process. The post-annealing was conducted at 550 °C for 1 hour under H_2 (3%) + Ar atmosphere to improve the superconducting properties.

The post-annealed Nb/MgB_2/SS304 specimen showed the T_c of 33.5 K and J_c of 1.4×10^5 A/cm^2 at 20 K and 5 T. Crystallinities, microstructures, and interfacial reactions will be also discussed.

[1] S. Horii et al., APEX 11 (2018) 093102

WBP2-4

Research and Development of the LTS and HTS Superconductors at SC "VNIINM"

ILDAR M. Abdyukhanov[1], Alexander G. Silaev[1], Mikhail M. Potapenko[1], Victor I. Pantsyrny[1], *Maxim V. Alekseev[1], Yuriy V. Karasev[1], Valery A. Drobyshev[1], Marina V. Kravtsova[1], Anastasiia Tsapleva[1], Konstantin A. Mareev[1], Maria V. Krylova[1], Pavel A. Lykianov[1], Maria V. Polikarpova[1], Ilya I. Savelyev[1], Vadim Y. Korpusov[1], Nikolay I. Salunin[1], Igor N. Gubkin[1], Evgeny V. Nikulenkov[1], Anton V. Malchenkov[1], Dmitry N. Rakov[1], Yulia N. Belotelova[1], Pavel V. Konovalov[1], Elena V. Kotova[1]

SC A.A. Bochvar High-Technology Research Institute of Inorganic Materials, Russia[1]

SC "VNIINM" is the only developer of the technical low-temperature superconducting strands in Russia especially on the base of Nb_3Sn phase and NbTi alloy. NbTi strands for the Tokamak-7, Nb_3Sn strands for the Tokamak-15, Nb_3Sn and NbTi strands for the ITER, NbTi strands for accelerator NICA, pilot batch of Nb_3Sn strands for the LHC upgrade and other projects were produced in industrial conditions using technologies of SC "VNIINM" and by its scientific support. All the strands produced met technical specifications. At present Bochvar Institute develops layout and production technology of Nb_3Sn strands for FCC. SC "VNIINM" have production technologies of the targets and substrate tapes for the HTS-2 and develops MgB_2 superconductors.
Characteristics of the superconductors developed at SC "VNIINM" for the different projects and also targets and substrate tapes for the HTS-2 are reviewed in the paper. The ways of their current-carrying capacity enhancement are discussed.

Keywords: Nb3Sn, NbTi, strand, HTS

WBP2-5

Influence of Hf diffusion for strain effect of Hf doped Nb_3Sn wires

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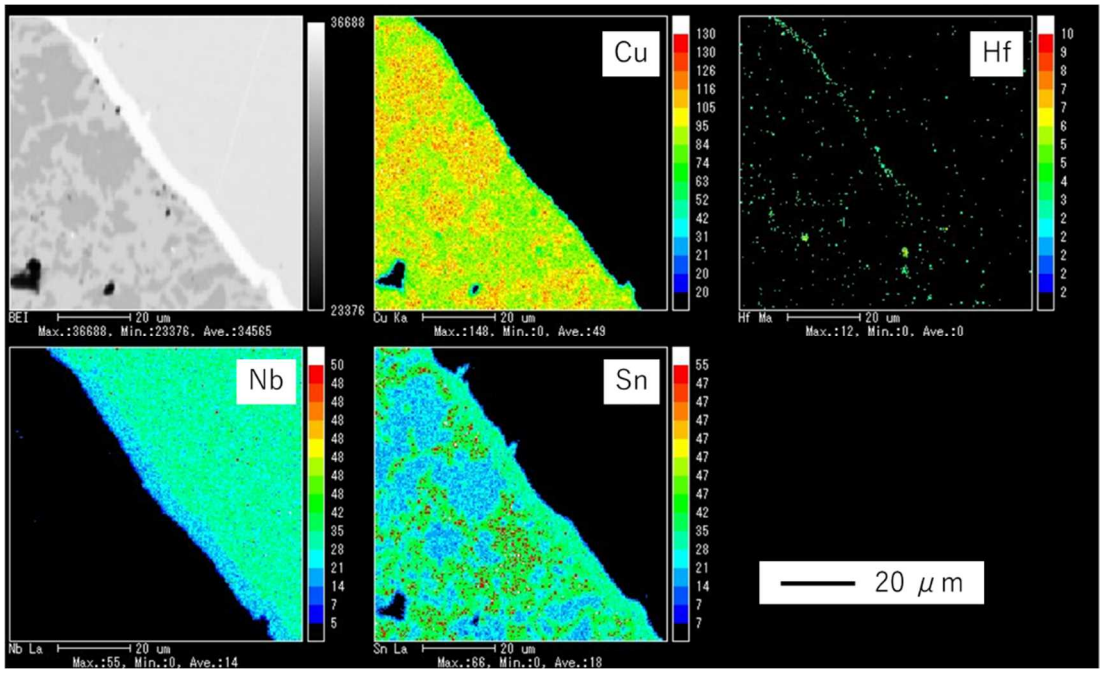
A Nb_3Sn wire have good superconducting properties at high magnetic fields. However, the superconducting properties of Nb_3Sn wires are very sensitive to stress and strain [1]. It is well known that the critical current of Nb_3Sn wires can be significantly increased by third elements addition [2]. The detailed relationship between the strain effect and third elements are not understood.

In this study, the Nb_3Sn wires with the third element were fabricated through Powder in Tube method. Tensile strain dependence of superconducting properties and the element mapping of cross sections for $(Nb,Hf)_3Sn$ wires were measured. 0.5 ,1.0 and 2.0at%Hf Nb_3Sn wires which have 1.5 mm diameter were prepared. Those wires were heat-treated at 670 or 800℃ for 100 h. EPMA composition mapping on the cross section of the 2.0at%Hf doped Nb_3Sn wire with heat treatment of 670 ℃ for 100 h are shown in Fig.1. This result shows that a Hf-Nb-Sn compound was observed at the boundary between the Nb_3Sn and the Cu-Sn-Hf region.



Keywords: Nb3Sn wires, strain effect, diffusion, third element

WBP3-1

Fabrication and Characterizations of $KCa_2Fe_4As_4F_2$ Superconducting HIP Wires

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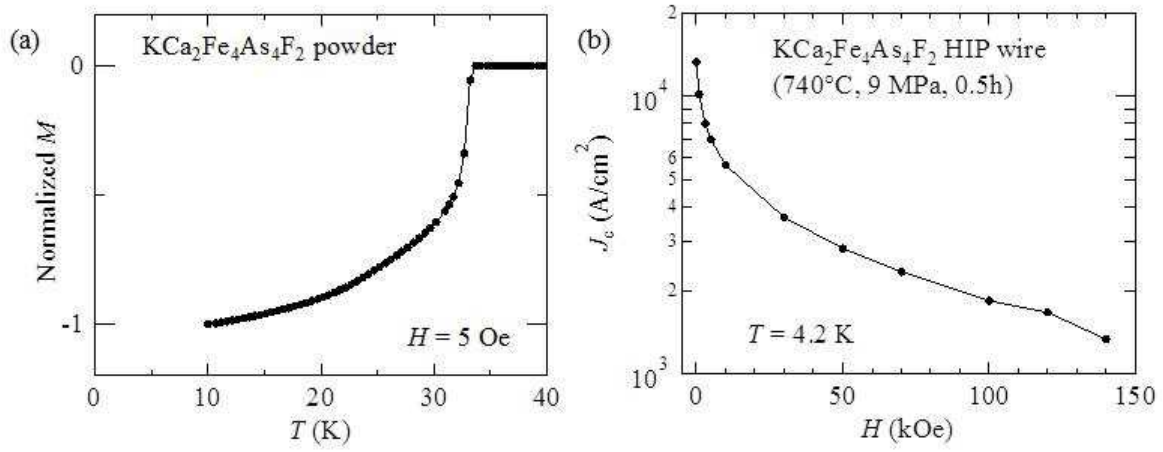
Iron-based superconductors (IBSs) are one of the promising candidates of future high-magnetic-field applications because of their high critical temperature, T_c, high critical current density, J_c, and high upper critical field, H_{c2}. Most of researches on IBS wires and tapes have been conducted using 122-type compounds ((Ba,K)Fe_2As_2 or (Sr,K)Fe_2As_2), and a practical level of J_c above 100 $kAcm^{-2}$ has been achieved in these wires and tapes. On the other hand, other IBS compounds are still investigated as raw materials for superconducting wires and tapes, such as $SmFeAsO_{1-y}$ and $CaKFe_4As_4$, whose J_c at 4.2 K in self-field are approximately 40 and 90 $kAcm^{-2}$, respectively. Here, we report the fabrication and characterizations of $KCa_2Fe_4As_4F_2$ round wires for the first time. Polycrystalline $KCa_2Fe_4As_4F_2$ powder was prepared by solid-state reaction and its T_c was evaluated from magnetization measurement as shown in figure (a). Superconducting wires were fabricated by powder-in-tube (PIT) method and hot-isostatic-press (HIP) technique. The self-field J_c of the $KCa_2Fe_4As_4F_2$ HIP wire fabricated at 740°C under a high pressure of 9 MPa for 0.5h, exceeded 10 $kAcm^{-2}$ as shown in figure (b). Details of the optimization of the round wire to achieve large J_c values and extensive characterizations of wires using X-ray diffraction and magneto-optical imaging will be presented.



Keywords: Iron-based superconductor, Critical current density, PIT-HIP wire, KCa2Fe4As4F2

WBP3-2

Effect of the metallic oxide mix-doping on the microstructure and superconducting properties of Bi-2223 Ag/tapes

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The Bi-2223 Ag/tapes with the composition $Bi_{1.8}Pb_{0.4}Sr_{1.9}Ca_{2.1}Cu_{3.5}O_y$ + Xn (X1: un-doped; X2: 1wt% MgO + 1wt%Ag_2O mix-doped; X3: 1wt% MgO + 1wt%Ag_2O + 0.05wt%SnO_2 mix-doped; X4: 1wt% MgO + 1wt%Ag_2O + 0.05wt%B_2O_3 mix-doped; X5: 1wt% MgO + 1wt%Ag_2O + 0.05wt%Li_2O; X6: 1wt% MgO + 1wt%Ag_2O + 0.05wt%La_2O_3 mix-doped) were prepared by sintering at 837℃ for 120 h after partial-melting at 850℃ for 1 h. The B_2O_3 mix-doping (X4) and B_2O_3 mix-doping (X5) decrease the conversion of Bi-2212 phase to Bi-2223 phase. However, the SnO_2 mix-doping (X3) and La_2O_3 mix-doping (X6) increase the conversion of Bi-2212 phase to Bi-2223 phase in comparison with the un-doping (X1). The tape with 1wt% MgO + 1wt%Ag_2O + 0.05wt%La_2O_3 mix-doping shows the highest proportion of Bi-2223 phase and the highest critical current density.

Keywords: Bi-2223, mix-doping, microstructure, superconducting

WBP3-3

Bi2212 precursor powder and Bi2212 wires synthesized based on nanospray combustion technology

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Nanospray combustion technology is an attractive way to make Bi2212 precursor powder for both its time-saving process and its good property in powder as well as in wires made by the powder. By adjusting the related parameters of nanospray combustion technology, mainly including the concentration of the Bi2212 precursor liquid, the flow rate of the carrier gas and the combustion temperature, we had synthesized Bi2212 precursor powder. By optimizing the related parameters, Bi2212 precursor powder with smaller particle size, good compositional uniformity and phase purity was obtained. Preliminary results showed Bi2212 wires synthesized based on this powder held a nearly equivalent Ic with the wires made based on the co-precipitation powder. It's believed that wires with improved performance would be obtained by using the precursor powder synthesized by the nanospray combustion technology in the near future.

Keywords: Nanospray combustion technology, Bi2212 precursor powder, Bi2212 wires

WBP3-4

Development of Bi-2223 high temperature superconducting tapes in NIN

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Bi-2223 high temperature superconducting tapes are called the First generation High temperature Superconductors (HTS) based on their sophisticated fabrication technique and stable mechanical structures. So far, there have already been many demonstration projects successfully proved the reliability of Bi-2223 HTS tapes. Therefore, the development of the fabrication technique is very important for the further improvement of superconducting related techniques. Northwest Institute for Non-Ferrous Metal Research (NIN) started the study of Bi-2223 tapes since 1990s. Recently, new improvements based on the novel spray pyrolysis techniques for precursor powders fabrication, the introduction of groove rolling process into cold working process, as well as the investigation and optimization of rolling process have been achieved and the current capacity of Bi-2223 tapes has been enhanced. Comparing with the traditional coprecipitation process we adopted for nearly 20 years, the spray pyrolysis technique exhibits many advantages, such as high uniformity of particle size and chemical composition, large production capability and short process path, which can all be beneficial to the industrial fabrication of precursor powders. So with the optimization of many important parameters, including pyrolysis temperature, airflow rate, and concentration of precursor solution, the critical current Ic of Bi-2223 tapes with spray pyrolysis powders has been improved from 80 A to 110 A.On the other hand, groove rolling process has completely different deformation mechanism with traditional drawing process, which is beneficial to the enhancement of filament density, and the uniform deformation of wires. Therefore, by introducing groove rolling process to replace certain steps of drawing process, the filament density has been improved for nearly 10%, and the enhancement of critical current for nearly 20% has been obtained.Finally, the optimization of rolling parameters, for example starting wire diameter and rolling passes have both been completed. And with the enhancement of filament texture, the current capacity of obtained tapes has been further enhanced. The maximum engineering critical current density Je of 10 kA/cm-2 has been obtained with the heat treatment performed under ambient pressure.

Keywords: Bi-2223, High temperature superconductor, Precursor powder, Groove rolling

WBP3-5

Fabrication of (Ba,Na)Fe_2As_2 round wires and tapes using HIP process

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Iron-based superconductors have high critical current density under high magnetic fields, and are expected to be applied as wires under high magnetic fields. Among them, researches on the wires of K-doped 122-based iron-based superconductors have been extensively advanced. In recent years, researches on wires and tapes of Na-doped (Sr,Na)Fe_2As_2 and (Ba,Na)Fe_2As_2 have been undertaken [1], and we have reported a record-high value of critical current density (J_c) of 40 kA/cm^2 at 100 kOe in (Ba,Na)Fe_2As_2 round wire [2].

In the present study, we fabricated round wires and tapes of (Ba,Na)Fe_2As_2 using HIP (hot isostatic press) process, and evaluated their transport J_c. Polycrystalline powders were synthesized by using pre-synthesized precursors (BaAa, NaAs, Fe_2As), which is simpler than the method of mixing raw materials in a planetary ball mill. Compared with the transport J_c (95 kA/cm^2 under self field, 40 kA/cm^2 at 100 kOe) of the wire in the previous study [2], the transport J_c of the present HIP round wire is higher at self-field (129 kA/cm^2), but slightly lower at 100 kOe (37 kA/cm^2) as shown in the figure. In addition to the results of the round wire mentioned above, we plan to discuss detailed characterizations of the tape fabricated from the same powder. In particular, X-ray diffraction is extensively applied to the evaluation of the degree of texturing of the wire and tape.

[1] Suwa *et al.* , Appl. Phys. Express **11**, 063101 (2018).
[2] Miyawaki *et al.*, 74th Annual Meeting of the Physical Society of Japan 16pS305-8 (2019).

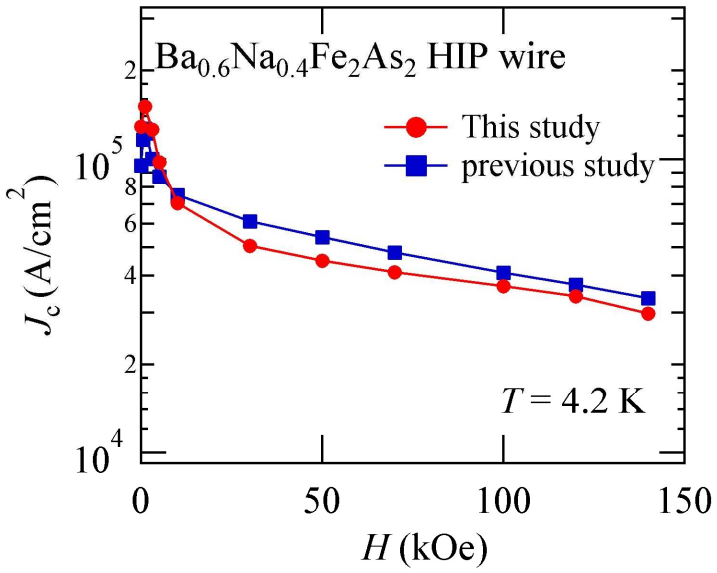

Figure. Magnetic field dependence of transport J_c of Ba0.6Na0.4Fe2As2 HIP round wires in this study and previous study [2].

Keywords: Iron-based superconductor, Critical current density, HIP round wire, HIP tape

WBP4-1

Evaluation of Critical Current Superconducting Junction with a Crack by Using FEM

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Railway Technical Research Institute, Tokyo, Japan[2]

The junction of the superconducting wires is considered to exhibit a current density distribution different from that of normal superconducting wires, and a stress distribution when receiving a force. Understanding them is essential in designing an applied device. When the junction receives an external force, damage such as cracks may occur. The current density distribution should also be considered when the superconductor wire is defective.

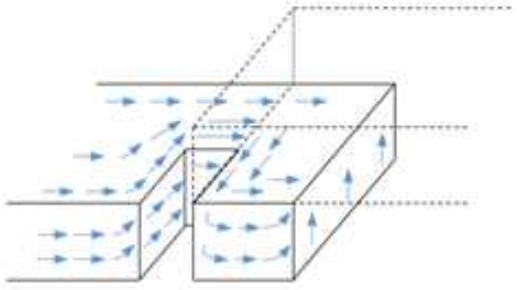
In this study, in order to clarify the electrical and mechanical properties of the junction of superconducting wires, the junction is numerically simulated using the finite element method (FEM) (the simulation tools are JMAG-Designer 17.0 and COMSOL Multiphysics®), and electrical and mechanical properties were evaluated.

We used a 1 μm thick YBCO superconducting film to act as a superconducting wire and jointed two such films together for current density simulation. The analysis was conducted from the left of the model by passing current, calculated using the finite element method, and revealed the current density distribution of the cross section. As shown in Fig. 1, the calculation in the case where there is a crack in the film in the vicinity of the junction was similarly performed. Magnetic field dependence of the critical current density is based on the experimental results of $YBa_2Cu_3O_{7-\delta}$.

Fig. 1 shows the flow direction of the current around the crack. The current density is concentrated on the other side of the crack, which makes the critical current of the superconducting film small. In other words, the maximum current that the superconducting wire can withstand becomes smaller.

Fig. 2 shows the *E-J* characteristics on the superconducting film with various crack width. It is found that the critical current is drastically reduced by increasing the width of crack.

This work was supported by JSPS KAKENHI Grant Number 19H00771.



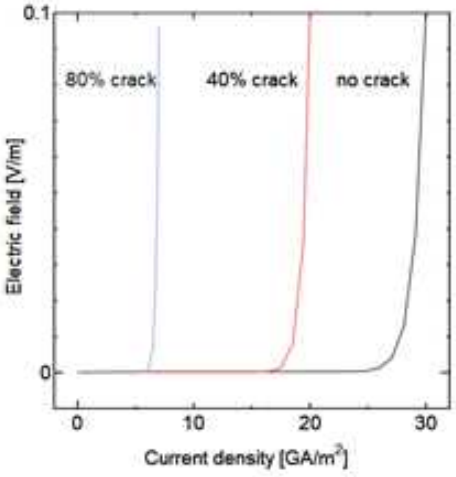


Fig. 1 Superconducting layer with a crack. The arrows indicate the direction of current density.
Fig. 2 *E-J* characteristics on the superconducting film with various crack width.

Keywords: Critical current density, Superconducting joint

WBP4-2

Peculiarities of dissipative phenomena in coated YBCO tapes carrying constant current during flux creep

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The effect of flux creep on the dissipation phenomena in tapes based on YBCO leading to the essentially nonlinear voltage-current characteristic of a superconductor is discussed. The obtained results are compared with the calculations, made in the framework of the existing thermal stabilization theory based on the model assuming jump transition from a superconducting state to a normal one. It is shown that this model incorrectly describes the dissipation states in a temperature range up to the critical temperature of the superconductor. It is shown that the type of nonlinearity of VCC has a significant effect on the dissipative phenomena in tapes. As a result, the allowable currents stably flowing in superconducting tapes may be higher than a priory defined critical current determined for continuously increasing voltage-current characteristic. Therefore, the critical current of high-T_c superconducting tapes, which is determined using continuously increasing voltage-current characteristic, has no physical meaning. Accordingly, fundamentals of the thermal stabilization theory must consider real temperature dependence of the dissipation energy in high-T_c superconducting tapes, which is a function of nonlinearity of their voltage-current characteristic.

WBP4-3

Numerical Study on AC Loss Properties of Two-Layer REBCO Power Cable by 3D Finite Element Method

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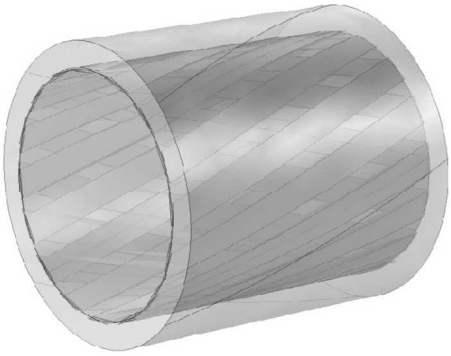
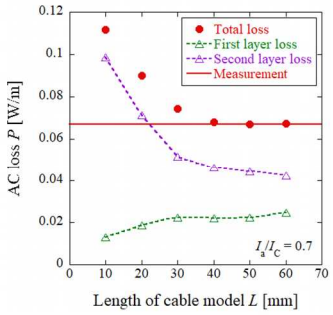
This study investigates the loss properties in a two superconducting-layer REBCO power cable fabricated by researchers at Furukawa Electric Co. Ltd. The losses were calculated by a three-dimensional finite element method (3D FEM) using COMSOL, which is based on H formulation without the thin-strip approximation of the superconductor. Fig. (a) shows the cable model which has the helical pitches of first layer and second layer are 340 mm (S-direction) and 280 mm (Z-direction), respectively. Fig. (b) plots the losses as functions of length of the cable model, fixing the normalized current $I_a/I_C = 0.7$. Here, I_a and I_C are transport current and critical current of the cable. As the length of cable model L is too short, a layer current of the outer layer is calculated as high, then a layer loss of the outer layer is obtained as high. Therefore, a total loss becomes large in comparing with a measurement. To get an accurate calculation, it is found that the L should be longer than 40 mm in this cable. Fig. (c) plots the total losses of the cable as functions of I_a/I_C, fixing $L = 40$ mm. As cab be seen, the calculated value is almost equal to the measurement.
Fig. (a) Model of two-layer cable, (b) AC losses versus length of cable model, (c) Comparison with measurement and calculation of AC loss of two-layer cable.



(a)



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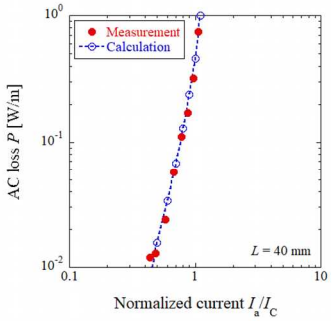

(c)

Keywords: AC loss, REBCO power cable, 3D FEM, EC model

WBP4-4

Evaluation of SUperconductive Assisted Machine (SUAM) with Superconducting Coated Wires using Finite Element Method

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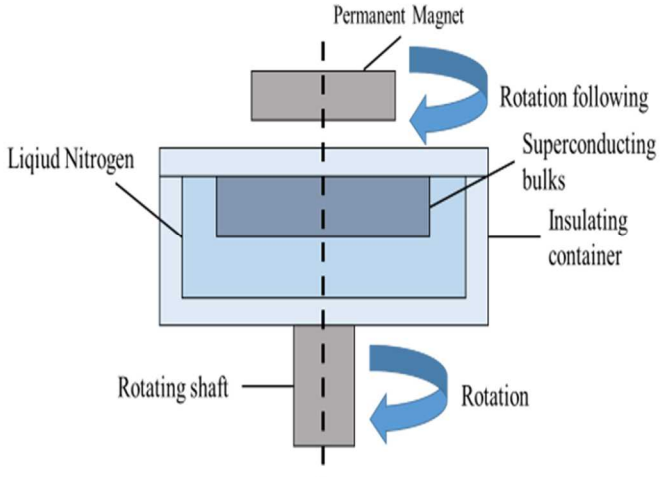
Various processing methods are used including lathe processing and magnetic polishing. At the present time, it is difficult to apply the hollow processing method to complicated shapes due to the restriction of the interference of tools as machining. In order to solve these problems, we have developed SUperconductive Assisted Machining method (SUAM) using the flux pinning phenomenon of bulk superconductors as shown in Fig.1. This SUAM is composed of a single-sided four-pole permanent magnet and a superconducting bulk, and is a method utilizing magnetic levitation that occurs when cooled in a magnetic field with the permanent magnet held in the air. In this method, the superconductor receives attractive, repulsive, restoring and driving forces. In this study, we evaluate these performances of the superconducting coated wire numerically using the finite element method, and compare with the superconducting bulk at each force.

We use JMAG to calculate by FEM, and use an *n*-value model to calculate the *E*-*J* characteristics. We use the experimental result of $GdBa_2Cu_3O_{7-\delta}$ superconducting bulk for the bulk and the experimental result of $YBa_2Cu_3O_{7-\delta}$ for the superconducting wire for the magnetic field dependence of the critical current density. We bring a 450 mT permanent magnet close to the superconducting bulk or superconducting wire at a speed of 0.1 mm/s. We make the superconducting wire into a laminated structure and calculate the total force of the force received by laminating 2 μm thick superconducting 20 layers.

Fig.2 shows the difference in repulsive force between the superconducting bulk and the superconducting coated wire. The repulsive force increases as decreasing the distance to the permanent magnet. As a whole, the superconducting coated wire has a smaller repulsive force than the superconducting bulk. About the attractive force and the rotational torque, the superconducting bulk similarly gives larger force. It is considered that a larger force can be obtained by increasing the number of superconducting coated wires.

This work was partly supported by JSPS KAKENHI Grant Number 19H00771.



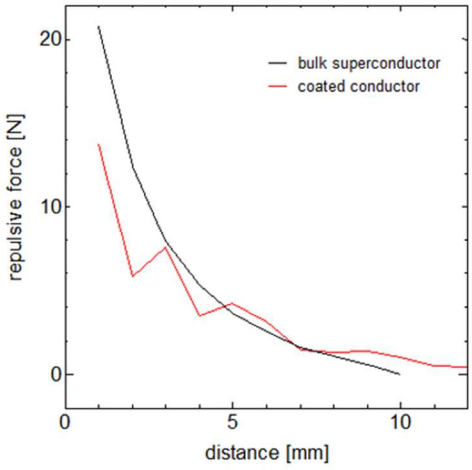


Fig.1 SUAM(SUperconducting Assisted Machine)
Fig.2 Difference in repulsive force between bulk supercondcting and coated conductor

Keywords: FEM, SUAM, magnetic levitation, coated conductor

WBP4-5

3D Numerical Study on Magnetization Losses in Twisted Soldered-Stacked-Square (3S) HTS wires

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Magnetization loss is an important parameter in the design of high temperature superconductivity (HTS) power devices. In order to reduce magnetization loss, a novel soldered-stacked-square (3S) HTS wire with 1 mm width is firstly proposed and manufactured by our group. In previous work, numerical and experimental results have shown the magnetization loss in the 3S wire is one order smaller than that in the original 4 mm tape with similar critical current under perpendicular magnetic field. However, unexpected large eddy current loss and coupling loss will be generated under parallel field. Therefore, the 3S wire has been twisted in this paper to further reduce the magnetization loss. Firstly, a three-dimensional (3D) numerical model is built for calculating the magnetization loss of the twisted 3S wire. Then, the frequency dependence and structure dependence of the twisted 3S wires are also been evaluated. Finally, the magnetization loss in the twisted 3S wire are compared with that in the original 3S wire to verify whether twisting could reduce the magnetization loss.

Keywords: 3D numerical model, 3S wires with 1 mm width, magnetization loss, twisting

WBP5-1

Effects of growth temperature and laser repetition rate on the shape of nanorods in $BaSnO_3$-doped $SmBa_2Cu_3O_y$ films prepared by pulsed laser deposition method

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$BaSnO_3$ (BSO) is one of the APC materials, which are known to grow up as nanorods in REBCO. Although a large number of studies have been performed on BSO-doped REBCO films, it has not been fully clarified about relationships between shape of nanorods and growth conditions such as substrate temperature (T_s) and laser repetition rate (f_L) in pulsed laser deposition (PLD) method. According to our previous simulation results, T_s and f_L have some effects on shape of nanorods. The purpose of this paper is to clarify effects of T_s and f_L on the shape of BSO nanorods and the superconducting properties, experimentally.

Using 2 vol% BSO-mixed SmBCO target, BSO-doped SmBCO films were prepared on CeO_2 buffered IBAD-MgO by PLD method, T_s is 800, 820, 840°C and f_L is 2, 5, 10, 20 Hz, respectivity. J_c versus magnetic field applied angle (J_c-θ) was measured at 77 K for the field of 1 T and 65 K for the field of 3 T. We defined the term J_c^{min} as the lowest value of the J_c-θ curves. In order to consider the shape of nanorods, we evaluated the J_c^{min} and $J_c(B//c) / J_c(B//ab)$ *depending on* T_s *and* f_L.

Fig. 1 shows the contour plot on (a) J_c^{min}, and (b) $J_c(B//c) / J_c(B//ab)$ depending on T_s and f_L at 65 K in 3 T. In Fig. 1(a), J_c^{min} has a maximum value when T_s was 800°C and f_L was 20 Hz, and as T_s became larger and f_L became lower, the value tended to decrease. This result indicates that isotropic flux pinning is achieved in the film deposited at low T_s and high f_L. On the other hand, in Fig. 1(b), $J_c(B//c) / J_c(B//ab)$ showed a maximum value when T_s was 840°C and f_L was 2 Hz, and as T_s became lower, the value tended to decrease. This result indicates that c-axis correlated pinning centers are included in the film deposited at high T_s and low f_L. From these facts, we argued that straight BSO nanorods along the c-axis of SmBCO grow in the films deposited at high T_s and low f_L, in contrast, short and inclined BSO nanorods grow in the films deposited at low T_s and high f_L. This tendency is almost the same with the previous simulation result. These results clearly show that the shape of nanorods can be controlled by T_s and f_L. We will compare this result with the films doped with other BMO materials.

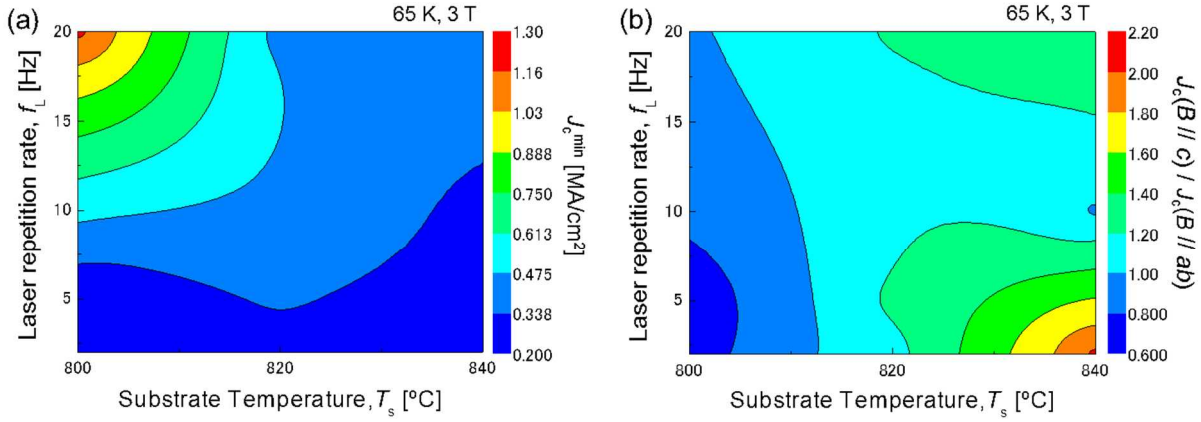

Fig.1 Contour plot of (a) J_c^{min}, and (b) $J_c(B//c) / J_c(B//ab)$ depending on substrate temperature T_s and laser repetition rate f_L at 65 K in 3 T.

(1) This work was partly supported by JSPS (19K22154), JST-ALCA, and JST-A-STEP.
(2) The metal substrates were provided by Dr. Y. Iijima of Fujikura Ltd.

Keywords: nanorods, REBCO, Artificial pinning center, Pulsed laser deposition

WBP5-2

Thickening of $YBa_2Cu_3O_y$ coated conductors fabricated by self-heating technique in Pulsed Laser Deposition method and evaluation of the superconducting properties

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$REBa_2Cu_3O_y$ (REBCO) coated conductors (CCs) are expected for high critical currents (I_c). In order to improve the I_c, it is essential to increase the film thickness while maintaining the high critical current density (J_c). However, it has been reported that *a*-axis oriented grains as the film thickness increases are generated and J_c decreases[1]. The occurrence of *a*-axis grains is due to the decrease in surface substrate temperature during the deposition. Thus, many research groups have developed the method of a heating substrate. For example, one of the methods is self-heating (S-H) technique. This technique is a method to heat the substrate by the Joule effect. The system provides rapid thermal response compared with the conventional heating system that heats the substrate with a heater[2].

In this study, we fabricated $YBa_2Cu_3O_y$ (YBCO) CCs on IBAD-MgO substrates which were heated by S-H technique in pulsed laser deposition (PLD) method. A thermocouple temperature ($T_{T.C.}$) was measured by attached thermocouple to substrate. $T_{T.C.}$ was maintained by proportional-integral-derivative (PID) control during the deposition. For comparison, YBCO CCs without PID control are also fabricated. We fabricated a thick film of which thickness was about 0.9 - 8.6 μm was prepared under the conditions of $T_{T.C.}$ = 758 and 783 °C, oxygen partial pressure P_{O2} = 200 mTorr, and laser energy density D = 1.5 J/cm^2.

Fig. 1 shows thickness dependence of I_c deposited at different $T_{T.C.}$. It was confirmed that I_c was increased by PID control. I_c reached about 750 A/cm-width (77 K, self-field) and was saturated in the film at $T_{T.C.}$ = 758°C at the thickness of thicker than 4.9 μm. This result might show that dead layer including *a*-axis oriented grains and other phases is formed on the surface of the CCs in thickening. We will report the microstructure of pure YBCO thick CC and superconducting properties of $BaHfO_3$-doped YBCO thick film in magnetic fields.

This work was partly supported by JSPS (19K22154), JST-ALCA, and JST-A-STEP. The metal substrates were provided by Dr. Y. Iijima of Fujikura Ltd.

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[2] G. Majkic et al., IEEE Trans. Appl. Supercond. 25 (2015) 3

Keywords: Self-heating technique, PLD method, REBCO, YBCO

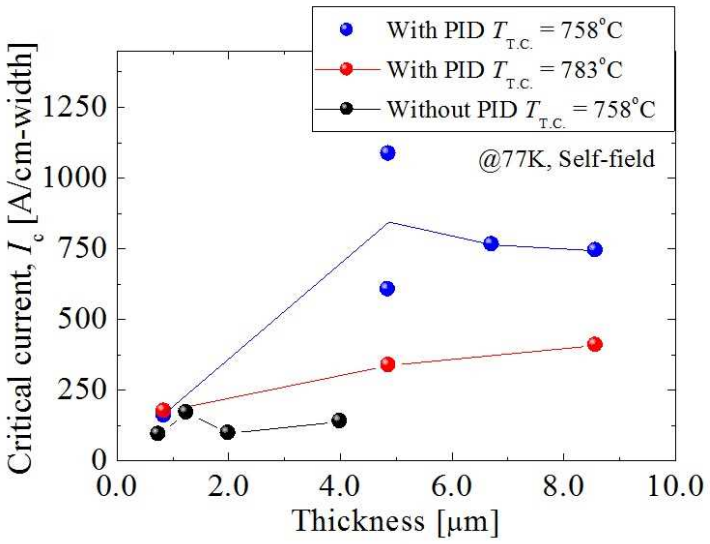

Fig. 1 Thickness dependence of I_c in YBCO CCs deposited at various $T_{T.C.}$s with and without PID control of substrate temperature

WBP5-3

Deposition of thick superconducting YBCO films using the surface laser heating

*Jin Matsuzaka[1], Yuji Tsuchiya[1], Yusuke Ichino[1], Yutaka Yoshida[1]

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Cost reduction for $REBa_2Cu_3O_y$ (REBCO) coated conductors (CCs) are of interest in the recent applications such as magnets and motors. Establishment a technology to fabricate the thick REBCO layer with the larger I_c is one solution to reduce the amount of the REBCO CCs. However, the thickness of the REBCO layer is usually limited less than 3 μm in the CCs because the superconducting property of the REBCO layer significantly degrades at the large thickness due to the *a*-axis-oriented grains [1]. The deposition of the REBCO layer at a sufficiently high temperature suppresses the *a*-axis oriented grains [2]. Therefore, various heating methods have been studied such as the hot wall heating [3], the direct resistance heating [4], and the laser heating [5]. In this work, we combined the conventional resistance heating with the laser heating to the surface of the CCs by using an infrared CW laser.

YBCO films were deposited on IBAD-MgO tapes using the pulsed laser deposition with a KrF excimer laser. During the deposition, the tapes were heated with a SiC heater and a diode laser (wavelength: 915 nm). To stabilize the absorption of the heating laser, the diode laser turned on when the REBCO seed layer with 500 nm thickness was deposited.

Fig. 1 shows the film thickness dependence of the ratio of the *a*-axis oriented grains for the YBCO CCs fabricated using only the SiC heater and both the heaters. As results, the *a*-axis oriented grains are suppressed with the laser heating. Furthermore, this method is effective to fabricate the 5 μm thick REBCO films. In the future, we plan to evaluate the properties of the fabricated CCs and to fabricate further thick films.

This work was partly supported by JSPS (19K22154), JST-ALCA, JST-A-STEP, the Amada foundation, and the NU-AIST alliance project. The IBAD-MgO metal substrates were provided from Dr. Y Iijima of Fujikura Ltd.

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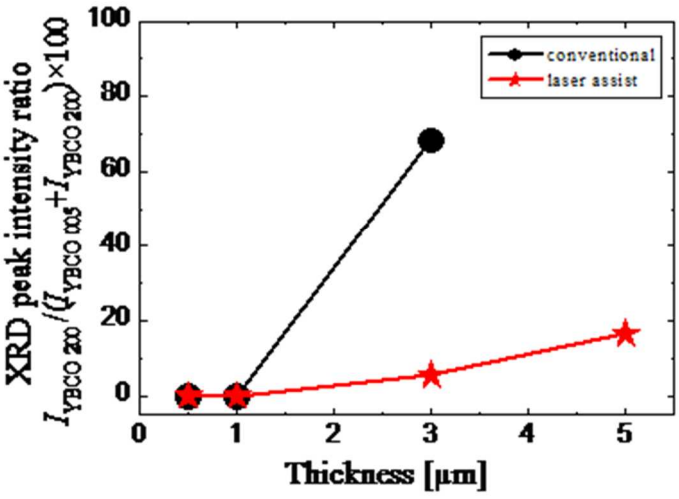

Fig. 1 The film thickness dependence of the ratio of *a*-axis oriented grains in the YBCO CCs fabricated with the conventional resistance heating and with the surface laser heating.

Keywords: YBCO, PLD, laser heating, thick film

WBP5-4

Fabrication of $BaTiO_3/YBa_2Cu_3O_y$ Multi-layered Films for Superconducting Capacitors

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High Q value is necessary for the wireless power transfer. The resistance in the circuit degrades the Q factor, thus it is important to use elements with a low internal resistance such as superconductor [1]. However, the reports on LC resonance using capacitors with superconductor are still few compared with the one with metal electrodes. Therefore, in this study, we fabricated multi-layered films with $BaTiO_3$ (BTO) films epitaxially grown on REBCO films for electrode as superconducting capacitors, and measured their dielectric properties. BTO is known as a material with an extremely high relative permittivity ε_r of more than 10,000, and epitaxially grows on REBCO because of its perovskite structure as same as REBCO [2].

Figure (a) shows the structures of the fabricated multi-layered films. 100 nm BTO films were deposited on a half area of 300 nm thick YBCO films grown on IBAD-MgO substrates by the PLD method. The YBCO and the BTO films are separately coated by two Ag electrodes with 8 mm^2 area using the sputtering. The equivalent circuit of the films are as follows; the capacitors with the YBCO superconducting electrode, the BTO dielectric, and the Ag metal electrode. The crystalline orientation of the film was evaluated by the XRD. The capacitance density C was measured at the room temperature (RT) and at 77 K by the four probe measurements using an LCR meter.

The XRD patterns of the films consisted of BTO (h00) peaks and YBCO (00l) peaks. Figure (b) shows the frequency f dependence of the impedance Z in the films at both the temperatures. Z at each temperature was sufficiently insulative of ~10 MΩ at ~ kHz, and was inverse proportional to f like a capacitance at f = 1~10 kHz. C of the films were 0.45 μF/m^2 at RT and 0.21 μF/m^2 at 77 K, and ε_r was 5.0×10^{-3} and 2.3×10^{-3}, respectively. The series resistance was too small to be measured, therefor we will investigate superconducting properties of the YBCO electrodes by using the magnetization measurement. We will also report on the capacitors using YBCO for both the electrodes.

This work was partly supported by JSPS (19K22154) and JST-ALCA, and JST-A-STEP. The metal substrates were provided by Dr. Y. Iijima of Fujikura Ltd.

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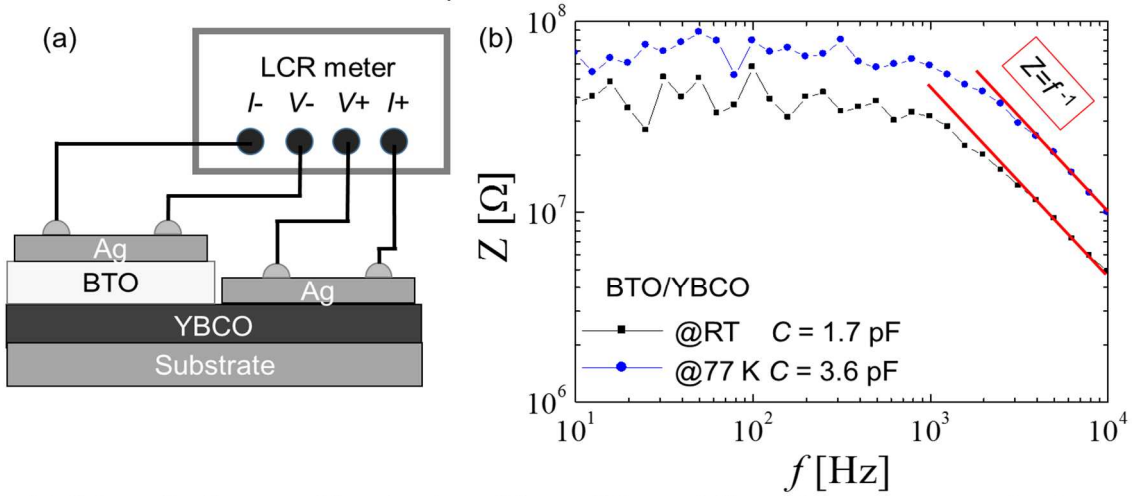

Fig. (a) Schematic diagram of the structure of the multi-layered film and the measurement set up. (b) Frequency dependences of impedance in the BTO/YBCO multi-layered films at RT and 77 K.

Keywords: REBCO, capacitor, BaTiO3, PLD

WBP5-5

The in-field J_c in RTR-PLD $EuBa_2Cu_3O_y$+$BaHfO_3$ coated conductors

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$REBa_2Cu_3O_y$(RE=Rare Earth: REBCO) coated conductors (CCs) derived from Reel-to-Reel Pulsed Laser Deposition (RTR-PLD) are promising to be valuable for magnet applications because of the high superconducting performance and reproducibility [1]. For practical applications, enhancement of the in-field J_c for RTR-PLD $EuBa_2Cu_3O_y$(EuBCO) CCs has been reported by the introduction of $BaHfO_3$ nanorods (BHO NRs) as flux pinning centers [2,3]. For further enhancement of the in-field J_c, understanding the effect of size, density, distribution and shape of the BHO NRs is very important.
In this work, in order to investigate the effect of BHO NRs on the in-field J_c, we prepared RTR-PLD $EuBa_2Cu_3O_y$(EuBCO) CC with various vol.% of BHO NR-doped EuBCO (EuBCO+BHO) CCs. Up to 3 vol.%, no degradation of T_c and self-field J_c are observed. The EuBCO+3 vol.%BHO CCs shows the highest in-field J_c and nearly isotropic angular dependence of J_c in this work. The mechanism of improvement of the in-field J_c by the addition of BHO NRs will be discussed based on crystallinity, transport properties and microstructure.

Acknowledgements: This work is supported by JSPS KAKENHI (17H032398) and Heiwa Nakajima Foundation. A part of this work was supported by JSPS KAKENHI (18KK0414), Kato Foundation for Promotion of Science (KJ-2744) and Promotion and Mutual Aid Corporation for private Schools of Japan (Science Research Promotion Fund).

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Keywords: Critical Current, RTR-PLD, BHO NRs, Coated Conductor

WBP5-6

Effect of laser energy and laser repetition frequency on BHO shape in PLD method

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For applications of $REBa_2Cu_3O_y$ (REBCO: RE = Rare Earth) high temperature superconductor, REBCO coated conductors (CCs) are required. Problems facing REBCO CCs are reducing production costs and improving critical current density (J_c) in magnetic fields isotropically. We have developed a technique called REBCO Growth using REBCO buffer layer (REGREB) technique which has made it possible to fabricate REBCO CCs with good performance at high production rate. There have been many reports that the J_c in magnetic fields have been improved by the introduction of artificial pinning centers (APCs). However, it is known that $BaHfO_3$(BHO), which is a typical APC, become *c*-axis correlated pinning centers. Therefore, we aimed to establish a technology to control microstructure by Pulsed Laser Deposition (PLD) method in order to improve J_c isotropically.

In this study, we focused on the relationship between laser repetition frequency (f_L) and laser energy (E_L) per pulse in the PLD method and the effect of these on the BHO shape was examined by changing f_L and E_L while keeping a high deposition rate.

Using a KrF excimer laser and a Reel to Reel system, BHO-doped $SmBa_2Cu_3O_y$ (SmBCO) CCs was fabricated on IBAD-MgO tape by the REGREB technique. Three samples were prepared, E_L was changed to 80, 90, and 100 mJ. In order to keep the deposition rate, f_L was set to 100, 70, and 64 Hz, respectively. The deposition rate was 13-18nm/sec.

Fig. 1 shows the angular dependence of J_c (J_c-q) at 77 K and 1 T. All three samples showed curves of almost the same shape. When E_L changes, the amount of evaporation per pulse and the kinetic energy of the evaporated particles would change. However, since the degree of supersaturation is high at the high deposition rate, it is considered that these changes due to E_L did not have a significant effect on the microstructure. Also, J_c peak at the B // c (q = 0°), which is often observed in the BHO-doped samples, was not confirmed. We speculated that the APC did not play *c*-axis pinning center.

We will compare the J_c-q curve at high and low deposition rate in order to clarify the effect of E_L.

This work was partly supported by JSPS (19K22154), JST-ALCA, and JST-A-STEP. The metal substrates were provided by Dr. T. Izumi, Dr. A. Ibi, and Dr. T. Machi of AIST.

Keywords: REBCO, BHO, Reel to Reel, PLD

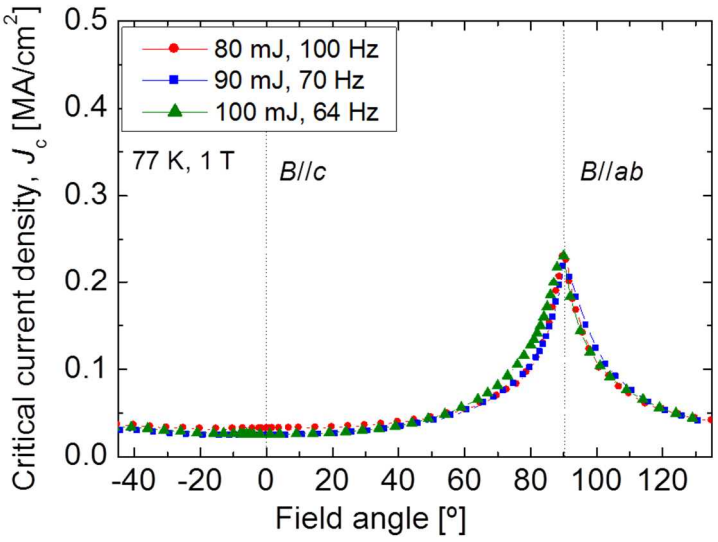

Fig. 1 The angular dependence of J_c (J_c - θ) at 77 K and 1 T.

WBP6-1

Improvement of critical current densities for Hf, Ce and La doped Gd123 thin film fabricated by fluorine-free MOD method

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Copper oxide superconductors have been expected for the next generation superconducting wire materials because of their high T_c and J_c in magnetic fields. In this study we have fabricated Hf, Ce and La doped Gd123 films by the fluorine-free MOD method to improve J_c. T_c indicated around 92 K and it didn't change for Hf and La doped films. J_c increased by about 63 % at 77.3 K and 1 T for 2 mol% Hf doped film than that for non-doped film. Furthermore we found the improvement of the crystal structure by La doping. Additionally, J_c indicated 3.10 MA cm^{-2} at 77.3 K and 0 T, and 0.32 MA cm^{-2} at 77.3 K and 1 T for 2 mol% Hf and 1 mol% La doped film. J_c increased by about 50 % at 77.3 K and 0 T for 2 mol% Hf and 1 mol% La doped film than that for 2 mol% Hf doped film. Jc increased by about 68 % at 77.3 K and 1 T for 2 mol% Hf and 1 mol% La doped film than that for non-doped film. We analyzed the density of effective pinning center (n_{eff}) according to the single vortex theory. n_{eff} indicated 7.74 m^{-2} and increased by about 95 % at 4.2 K for 2 mol% Hf doped film than that for non-doped film. In conclusion, the effective APCs in magnetic fields were introduced by Hf doping and the improvement of the crystallization was observed by La doping. We also have studied the optimization of the heat treatment condition and investigated the properties of Ce doped film to improve J_c further.

Keywords: fluorine-free metal organic deposition, GdBa2Cu3Oy, Hf, Ce and La doping

WBP6-2

Film thickness dependence of in-field J_c in (Y,Gd)BaCuO+$BaMO_3$ (M=Zr, Hf) nanoparticle CCs

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$REBa_2Cu_3O_y$ (REBCO) coated conductors (CCs) derived from the Trifluoroacetate-Metal Organic Deposition (TFA-MOD) process are a promising candidate for magnet applications because of the low-cost and the high critical current density (J_c). However, practical applications, such as MRI, generators, etc., require further enhancement of the in-field critical current (I_c). For high in-field I_c, increasing film thickness and the suppression of the formation of large second phase precipitates and uniform dispersion of pinning centers are important. So far, we have succeeded in obtaining high in-field I_c by controlling the crystal growth rate and introducing $BaZrO_3$ nanoparticles (BZO NPs) into the TFA-MOD $(Y_{0.77}Gd_{0.23})Ba_2Cu_3O_y$ (YGdBCO) CCs [1]. Recently, we have reported more improvement of in-field J_c by introducing $BaHfO_3$ (BHO) NPs instead of BZO NPs because of the former's higher NP density and smaller NPs size [2]. However, the effect of film thickness dependence of in-field J_c is not yet clear.

In order to investigate the film thickness dependence of the magnetic field (B) = 0.3 T, we prepared 12 vol.% BHO doped YGdBCO (+12BHO) CCs with various thicknesses. We found several common characteristics obtained in samples prepared by both pulsed laser deposition (PLD) and MOD REBCO CCs. For thinner films (d < 400 nm), a rapid decay of J_c (J_c μ $1/d^{0.5}$) is observed for with and without BHO NPs. For thicker films, the J_c value is almost constant. These thickness dependences of J_c may be caused by the change from 2D pinning to 3D pinning. We will discuss the influence of natural defects and BHO NPs on the thickness dependence of J_c in MOD-REBCO CCs based on a theoretical pinning model.

Acknowledgements: This work is supported by JSPS KAKENHI (17H03239). A part of this work was supported by JSPS KAKENHI (18KK0414), Kato Foundation for Promotion of Science (KJ-2744) and Promotion and Mutual Aid Corporation for Private Schools of Japan (Science Research Promotion Fund).

[1] M.Miura, Springer 2015 (ISBN:978-3-319-14477-1), chapter 1, pp.3-26
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Keywords: Critical Current, MOD, Thickness Dependence, Nanoparticle

WBP6-3

The influence of carrier density on the in-field J_c of (Y,Gd)BCO+BZO CCs

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Trifluoroacetate-metal organic deposition (TFA-MOD) produced $REBa_2Cu_3O_y$ (REBCO) coated conductors (CCs) are an important research subject because of the potential for low-cost and excellent superconducting properties. A high critical current density (J_c) in magnetic field for REBCO CCs is critical for magnetic applications. For the enhancement of the in-field J_c, there are two ways: 1) introducing pinning centers, and 2) carrier density control. So far, we have succeeded in obtaining higher in-field J_c by adding $BaZrO_3$ nanoparticles (BZO NPs) in TFA-MOD $(Y_{0.77}Gd_{0.23})Ba_2Cu_3O_{7-\delta}$ CCs ((Y,Gd)BCO+BZO) [1, 2]. However, the influence of the carrier density on the superconducting properties of TFA-MOD (Y,Gd)BCO+BZO CCs is not clear.
In this work, in order to investigate the influence of carrier density on superconducting properties, we fabricated $(Y,Gd)Ba_2Cu_3O_y$ and $(Y,Gd)Ba_2Cu_3O_y$+BZO CCs with various post annealing conditions. The (Y,Gd)BCO+BZO CC with optimum annealing conditions shows higher carrier density at 300 K and higher self-field J_c ($J_c^{s.f.}$) compared with that of other conditions. Moreover, the in-field J_c of (Y,Gd)BCO+BZO CC with optimum conditions is higher. We will discuss the mechanism of the improvement of the superconducting properties based on crystallinity, carrier density, critical temperature and self-field J_c.

Acknowledgements: This work is supported by JSPS KAKENHI (17H032398) and Heiwa Nakajima Foundation. A part of this work was supported by JSPS KAKENHI (18KK0414), Kato Foundation for Promotion of Science (KJ-2744) and Promotion and Mutual Aid Corporation for private Schools of Japan (Science Research Promotion Fund).

[1] M. Miura et al., *NPG Asia Materials* **9**, (2017) e447
[2] M. Miura et al., *Supercond. Sci. Technol.* **26** (2013) 035008.

Keywords: Critical current, O2 Anneal, BZO, TFA-MOD

WBP6-4

Investigation of interim heat treatment process on TFA-MOD method for production of $BaZrO_3$ added $REBa_2Cu_3O_y$ coated conductors with high in-field performance

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The trifluoroacetate metal-organic deposition (TFA-MOD) method has been commonly recognized as a low-cost technique for production of $REBa_2Cu_3O_y$ (RE: rare-earth, REBCO) coated conductors (CCs), and also considered as having a slightly lower superconducting property comparing with the CCs by the vapour method. On the other hand, low cost CCs with high performance in the magnetic-field have been required for electric power applications. In our previous study, we have developed two new techniques which were called interim-heat-treatment (IHT) [1] and ultrathin-once-coating (UTOC) [2] in order to enhance the in-field critical current density ($J_c(B)$) of $BaMO_3$ (M: metal element) added MOD-REBCO CCs, and achieved significant improvement of the $J_c(B)$ property of CCs. The IHT technique is a process to form an appropriate precursor film before the crystallization process of the REBCO, and the fundamental theoretical analysis of the IHT technique was previously reported [1]. In this study, we have investigated and optimized the effects of IHT atmosphere on the $J_c(B)$ performance of $BaZrO_3$ added $Y_{0.77}Gd_{0.23}Ba_2Cu_3O_y$ (YGdBCO/BZO) CCs. XRD measurements of the film after IHT at 580°C for 240 min under argon atmosphere confirmed the significantly coarsening of CuO. On the other hand, significantly coarsening of CuO was not observed in the film after IHT under oxygen atmosphere. The coarsening of CuO in IHT films is not good for obtaining high superconducting performance of YGdBCO/BZO CCs since that may cause of formation of *a*-axis orientation during the crystallization step [3]. The high $J_c(B)$ value at 77 K and 3 T ($B//c$) of >0.5 MA/cm^2 was obtained for YGdBCO/BHO CC with IHT at 580°C for 240 min under oxygen atmosphere.
This work was supported by the New Energy and Industrial Technology Development Organization (NEDO), Advanced Medical Services from the Japan Agency for Medical Research and development (AMED), and Ministry of Economy, Trade and Industry (METI).

[1] K. Nakaoka *et al.*, *IEEE Tran on Appl. Supercond.* **26** (2016) 8000304
[2] K. Nakaoka *et al.*, *Supercond. Sci. Technol.* **30** (2017) 055008
[3] K. Nakaoka *et al.*, *J. Physics: Conference Series* in press (2018)

Keywords: TFA-MOD process, interim-heat-treatment, REBCO

WBP7-1

Competing flux pinning of columnar defects in different directions for high-T_c superconductors

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We studied competing effect for flux pinning between columnar defects (CDs) along the *c*-axis and crossing at $\pm\theta_i$ relative to the *c*-axis in high-T_c superconductors, through the angular behaviors of critical current density J_c in $YBa_2Cu_3O_y$ thin films with the CDs installed by heavy-ion irradiations. A large enhancement of J_c centered at $B \mid\mid c$ occurs for the CD-configurations composed of CDs along the *c*-axis and with $\theta_i \leq \pm 60°$: the angular region where J_c is enhanced by CDs is more expanded for the CD-configuration with larger crossing angle $\pm\theta_i$, whereas the enhancement of J_c at $B \mid\mid c$ is slightly weakened. A J_c peak at $\pm\theta_i$, however, cannot be seen even for the film including CDs with $\theta_i = \pm 60°$. These results demonstrate that the synergy effect of flux pinning between CDs along the *c*-axis and with $\theta_i \leq \pm 60°$ can occur in angular range from $-\theta_i$ to θ_i, since the trapping angle of CDs along the *c*-axis is about 60°. In the vicinity of $B \mid\mid ab$, on the other hand, CDs in any direction hardly contribute to flux pinning for the CD-configurations with $\theta_i \leq \pm 60°$. For the CD-configuration composed of CDs along the *c*-axis and with $\theta_i = \pm 80°$, by contrast, the J_c drastically enhances around $B \mid\mid ab$: the J_c peak emerges at the two irradiation angles $\theta_i = \pm 80°$ and the value of J_c increases even at $B \mid\mid ab$ where the J_c shows not a peak but a dip behavior. The appearance of the J_c peak at $\theta_i = \pm 80°$ means that the CDs crossing at $\theta_i = \pm 80°$ contribute to the flux pinning independently from CDs along the *c*-axis, since the crossed CDs exist out of the trapping angle of CDs along the *c*-axis. On the other hand, there is a little enhancement of J_c with no peak around $B \mid\mid c$ even though the CDs are also installed along the *c*-axis: CDs in closer directions to the *ab*-plane induce sliding motion of flux lines along the CDs at $B \mid\mid c$, leading to the deterioration of flux pinning by CDs along the *c*-axis.

Keywords: high-Tc superconductors, critical current density, anisotropy, columnar defects

WBP7-2

TDGL Simulation of Critical Current Density introducing z axis Anisotropy γ_z

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The relationship between anisotropy strength and critical current densities J_c in small superconducting cube exposed to a transport current and a transverse magnetic field were investigated. The TDGL equations for the superconducting cube was numerically solved by using the Euler method. In this case, the vector potential $\boldsymbol{A}$ depends only on the external magnetic field $\boldsymbol{B}$. We show the three-dimensional dynamics of the quantized magnetic flux lines by plotting the contour surfaces of the superconducting electron density $|\Psi|^2$, where Ψ is the order parameter.

In this study, the parameters using in the original TDGL equations were normalized using the coherence length ξ and the upper critical field B_{c2} and so on for reducing the number of the constants in the TDGL equations.

We considered a superconducting cube of which side length is 10ξ in the vacuum. In addition, 4 columnar pins of diameter ξ were introduced with the distance d of pins as shown in Fig. 1(a). Here, we define the order parameter Ψ as 0 inside of the pins. We give the boundary condition corresponding to the normal component of the electric current density $\boldsymbol{J}$ is zero at the surfaces of the cube. $\boldsymbol{J}$ and $\boldsymbol{B}$ are applied to the y axis and the z axis, respectively. Hence, the vector potential can be given by $(A_x, A_y, A_z)=(0, Bx, 0)$ for the transverse magnetic field. The electric current density and the magnetic field at each time were kept constant at a normalized value.

Fig. 1(b), (c) and (d) shows the flux lines with different γz of columnar pins. Calculations were made with external magnetic field $B = 0.1, 0.2, \ldots, 0.6$, current density $J = 0.01, 0.02, \ldots, 0.30$, and z axis anisotropy strength $\gamma_z = 1, 2, 4, 8$.

Fig. 2 shows the numerical results of J_c - B at the z axis anisotropy strength $\gamma_z = 1, 2, 4, 8$. A large peak appears at $B = 0.4$. This is due to the peak effect. And there is almost no difference due to the strength of the anisotropy. Therefore, it was confirmed that the peak effect works similarly even when the z axis has anisotropy.

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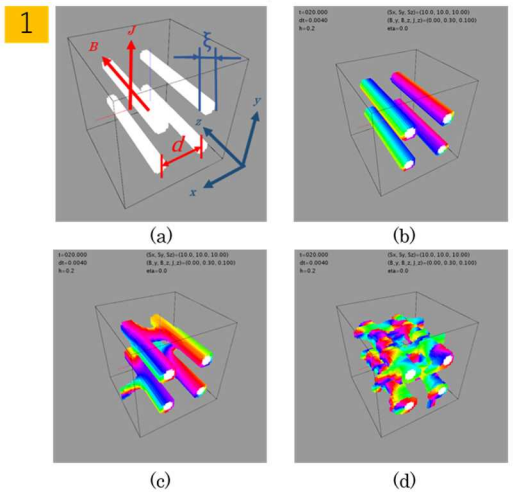

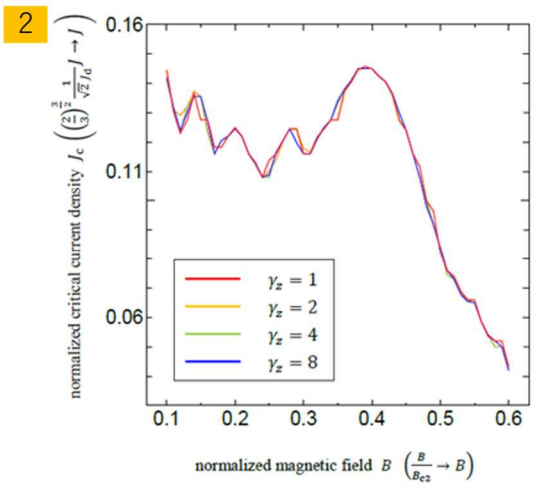

Fig. 1: (a) Geometry of the superconducting cube. Calculated results of flux lines for (b) $\gamma_z^2 = 1$, (c) $\gamma_z^2 = 8$ and (d) $\gamma_z^2 = 512$.
Fig. 2: Numerical results of Jc - B at the z axis anisotropy strength $\gamma_z = 1, 2, 4, 8$.

Keywords: Critical current density, time-dependent Ginzburg-Landau equations

WBP7-3

J_C control by hybrid pinning of nanorods and nanoparticles in $YBa_2Cu_3O_{7-x}$ film

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Improvement of critical current density (J_C) and suppression of J_C anisotropy are required to develop high performance $YBa_2Cu_3O_{7-x}$ (YBCO) tapes. While introduction of nanorods comprising of $BaZrO_3$, $BaSnO_3$, $BaHfO_3$ is effective for improving the J_C in magnetic fields, the nanorods result in anisotropic vortex pinning and significant J_C anisotropy. The J_C anisotropy should be reduced with maintaining high J_C in YBCO films. For this purpose, we prepared the YBCO films containing nanorods and nanoparticles to realize hybrid pinning, and investigated influence of the nanorod and nanoparticle distributions on J_C.

YBCO films were fabricated on $SrTiO_3$ substrate by PLD (Pulsed Laser Deposition) method. Here, BHO nanorods and Y_2O_3 nanoparticles were incorporated using the 6wt%BHO-doped YBCO target and Y_2O_3 sectors on targets (pure YBCO/YBCO+BHO targets), respectively. We prepared two types of samples of YBCO+BHO+Y_2O_3 films and YBCO+BHO/YBCO+Y_2O_3 films in addition to the YBCO+BHO single layer film (SL). The superconducting properties of fabricated samples were evaluated at 77 K, 65 K, 40 K and 20 K in magnetic fields.

At 77 K, the YBCO+BHO single layer showed F_{PMAX} = 25.1 GN m^{-3} (77 K, 5 T) which was higher than that for the YBCO films containing both nanorods and nanoparticles. However, at 20 K, F_{PMAX} = 806 GN m^{-3} (20 K, 12 T) which was the highest at 20 K among the present films was obtained in the YBCO+BHO+Y_2O_3 film. The J_C minimum was observed at 40°, and the J_C minimum was 1.67 $MAcm^{-3}$ and 3.58 $MAcm^{-3}$ for the YBCO+BHO+Y_2O_3 and the YBCO+BHO in a temperature of 20 K and a magnetic field of 16 T, respectively. The in-between value of 2.32 $MAcm^{-3}$ was observed for the YBCO+BHO/YBCO+Y_2O_3 films. By tuning the distribution of nanorod and nanoparticle, the J_C values and J_C anisotropy can be controlled in YBCO films.

Keywords: voltex pinning, YBCO

WBP7-4

Enhanced pinning properties by refining Gd_2O_3 particles trapped in the $GdBa_2Cu_3O_{7-\delta}$ films via RCE-DR

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Superconductor, Nano & Advanced Materials Corporation (SuNAM Co.) Ltd, Anseong, Korea[2]

The pinning properties of $GdBa_2Cu_3O_{7-d}$ (GdBCO) coated conductors(CCs) fabricated by reactive co-evaporation by deposition and reaction (RCE-DR) should be further improved because in-field critical current densities (J_c) properties of GdBCO CCs are relatively lower than those of REBCO CCs produced by other processes such as metal-organic deposition (MOD), pulsed laser deposition (PLD), metal-organic chemical vapor deposition (MOCVD). To improve in-field J_c of GdBCO CCs fabricated by the RCE-DR process, employing the nominal composition of Gd:Ba:Cu=1:1:2.5, we tried to refine the Gd_2O_3 particles trapped in the GdBCO superconducting matrix by controlling nucleation and growth rates of Gd_2O_3 in the liquid phase before crystallization of GdBCO. For this purpose, the processing conditions were carefully selected from the GdBCO stability phase diagram experimentally determined for the nominal composition of Gd:Ba:cu=1:1:2.5. By lowering the nucleation and growth temperature of Gd_2O_3 in the liquid from 860 to 800°C in the oxygen pressure of 20, 30 mTorr, the average particle size of Gd_2O_3 particles trapped in the GdBCO matrix could be refined from 137 ± 52 to 73 ± 31 nm, respectively. The pinning properties could be significantly improved by the refinement of Gd_2O_3 so that the refinement strategy might be applied to the RCE-DR process. Details will be presented for a discussion.

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Keywords: GdBCO, Gd2O3, Pinning properties, stabilitty phase diagram

WBP7-5

Effect of post-annealing on the pinning properties of $GdBa_2Cu_3O_{7-\delta}$ coated conductors via RCE-DR

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We investigated the effect of post-annealing on the pinning properties of $GdBa_2Cu_3O_{7-\delta}$ (GdBCO) coated conductors (CCs) fabricated by the reactive co-evaporation deposition & reaction (RCE-DR) process. On the basis of the stability phase diagram of GdBCO, as-grown GdBCO CCs were post-annealed at the temperatures ranging from 450 to 750℃ in various oxygen pressures. Interestingly, for the same P_{O_2} of 300 mTorr, the $GdBa_2Cu_4O_{16}$ (Gd124) phase was observable in the sample annealed at the temperatures lower than 600℃ while the density of stacking faults (SFs) was decreased in the samples annealed at the higher temperatures of 650 and 750℃. The pinning properties of post-annealed GdBCO samples were sensitive to the annealing conditions, including oxygen pressure, temperatures, and time. In comparison with as-grown sample, the minimum J_c values of samples annealed at 750℃ in the P_{O_2} of 300 mTorr for 5 min are improved at relatively low temperatures in high field region, which is due to a significant reduction in the density of SFs. On the other hand, the GdBCO CCs annealed 500℃ in the P_{O_2} of 300 mTorr for 1 h exhibit enhanced pinning properties at relatively high temperature in low field region, which is ascribed to the formation of Gd124 phase. Detailed relationship between microstructures and pinning properties will be presented for a discussion.

This work (Grants No.S2660496) was supported by project for Cooperative R&D between Industry, Academy, and Research Institute funded Korea Ministry of SMEs and Startups in 2018.

WBP7-6

Effect of growth condition on lattice strain of $SmBa_2Cu_3O_y$ films induced by $BaHfO_3$ nanorods

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$BaMO_3$ (BMO, M=Zr, Sn, Hf etc) self-organizes into a nanorod shape within $REBa_2Cu_3O_y$ (REBCO, RE=Y, Sm, Nd etc) films grown by vapor phase deposition method such as pulsed laser deposition (PLD). In order to improve flux pinning in a high magnetic field, it is necessary to introduce high number density of BMO. However, excess amount of the BMO causes T_c reduction due to lattice strain of REBCO induced by BMO nanorods. If the diameter of nanorods becomes smaller, we can expect that lattice strain become smaller. From our previous studies, diameter of BMO nanorods can be controlled by substrate temperature, deposition rate and volume fraction of BMO [1-3]. In this study, in order to control nanorods diameter and evaluate lattice strain, $SmBa_2Cu_3O_y$ (SmBCO) films including 16 vol% of $BaHfO_3$ (BHO) were prepared by low temperature growth (LTG) technique [3].

The BHO-doped SmBCO films were deposited on $LaAlO_3$(100) (LAO) single-crystal substrates using a conventional PLD method with a Nd: YAG laser. To control nanorod diameter, we used the LTG technique. In the LTG technique, a thin SmBCO layer (seed layer) was deposited at a relatively high substrate temperature (T_s) of 880ºC, and then a SmBCO layer (upper layer) was homo-epitaxially grown on the seed layer at 790ºC – 880ºC.

Fig. (a) shows critical current density (J_c) depending on magnetic field. From this figure, slope of the J_c-B curves is changed at a magnetic field and the magnetic field was defined as B_{end}. Except for 790ºC sample, B_{end} increased with decreasing T_s. This indicates that number density of BHO nanorods increased and the diameter of the BHO nanorods decreased due to constant volume fraction of BHO. Figs. (b) and (c) indicate lattice strain of REBCO and BMO as a function of T_s. Except for the 790ºC sample, with decreasing T_s, tensile strain applied to SmBCO reduced, on the other hand, compressive strain applied to BHO increased. It indicates that narrow nanorods grown at low T_s are easy to compress.

Figs. (a) J_c of SmBCO films as a function of magnetic field. T_s dependence of lattice strain (b) in SmBCO and (c) in BHO.

Acknowledgement: This work was partly supported by SPS (19K22154), JST-ALCA, and JST-A-STEP.

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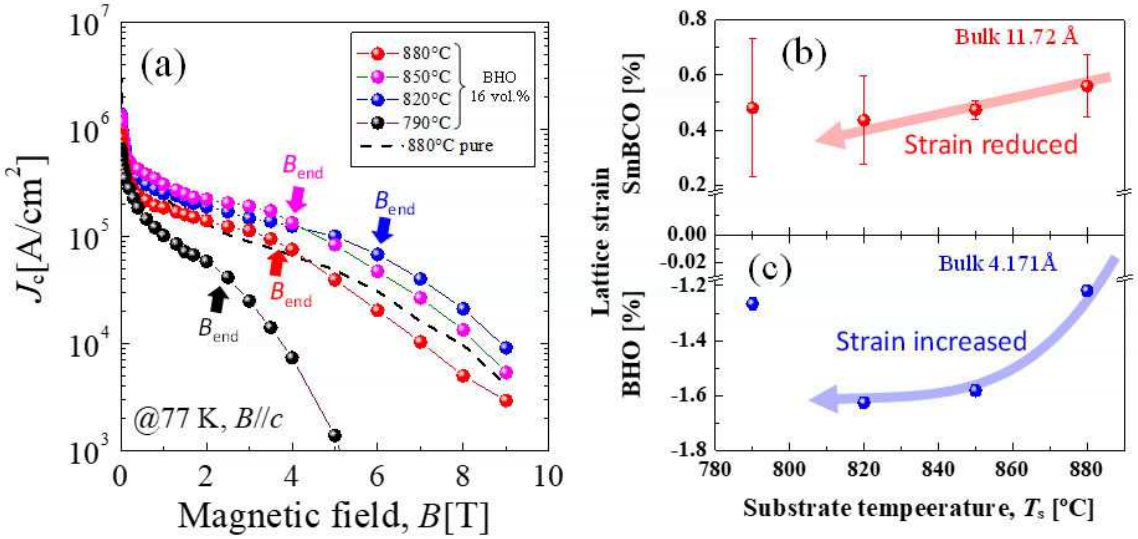

Keywords: SmBa2Cu3Oy, BaHfO3, nanorod, film

WBP7-7

Improvement of critical current asymmetricity in $BaHfO_3$-doped $SmBa_2Cu_3O_y$ superconducting films by ion milling etching

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$REBa_2Cu_3O_y$ (REBCO) high-temperature superconductor has a high T_c and is expected for various applications. Superconducting diodes with asymmetric I_c depending on the current direction have been proposed [1]. The previous studies clarify that the origin of the asymmetricity is the difference of I_c where the vortices penetrate from the film surface to the substrate or the opposite direction[1,2]. For practical application, the rectification rate needs to be improved. We have reported that the small surface roughness (δR) intensifies the asymmetricity [3].

In this study, the asymmetricity was improved by controlling the δR of the REBCO film by a post-treatment using the Ar ion milling.

$BaHfO_3$ (BHO)-doped $SmBa_2Cu_3O_y$ (SmBCO) films were fabricated on $LaAlO_3$ (100) substrates with a thickness of 400 nm by using the pulsed laser deposition method. Several samples were etched by the Ar ion milling. The etching rate and time was 15 nm/min and 4 min, respectively. The films were patterned into bridges with a width of 200 μm and a length of 1 mm. The asymmetricity was measured in an in-plane magnetic field of 0 to 0.4 T at 77.3 K. Fig. 1 shows a typical *I-V* characteristic in the etched sample. The schematic diagram in the figure shows the current and the magnetic field directions for the sample. I_c^{up} corresponds to I_c with the flux motion from the substrate toward the film surface and I_c^{down} is the one with the opposite polarity. Asymmetricity (*Asym.*) was defined by the following equation.

The maximum of *Asym.* for the magnetic field is defined as $Asym.^{max}$. Fig. 2 shows δR dependence of $Asym.^{max}$ at 77.3 K in the BHO-doped films. $Asym.^{max}$ tends to increase with decreasing δR. δR decreased by 20 nm and $Asym.^{max}$ increased by 2% for etching. The results indicate that the Ar ion milling enhances the asymmetry. We will discuss why δR reduction by Ar ion milling improves *Asym.* and will report the results for the inclined Ar ion milling.

This work was partly supported by JSPS (19K22154), JST-ALCA, JST-A-STEP, and Research Foundation for the Electrotechnology of Chubu.

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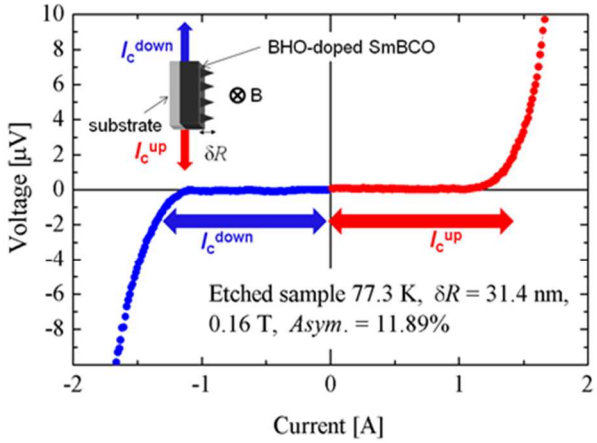

Fig.1 Typical *I-V* characteristics obtained at 77.3 K and 0.16 T in the etched sample.

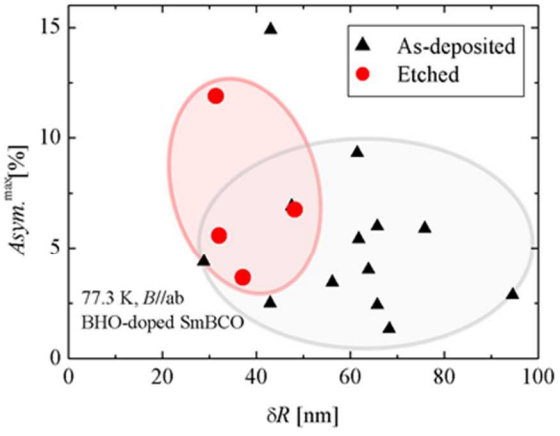

Fig. 2 δR dependence of $Asym.^{max}$ at 77.3 K for BHO-doped SmBCO.

Keywords: REBCO, diode, etching, asymmetricity

WBP8-1

Highly reinforced, low magnetic and biaxially textured super high tungsten Ni-W alloy composite substrates used in coated conductors

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Highly reinforced, low magnetic and biaxially textured super high tungsten Ni-W alloy substrates have been fabricated through composite substrate preparation method used in coated conductor applications. The content of tungsten exceeds 10% in the obtained substrates, which is the current world record. In this excellent super high tungsten substrate (Ni10W), it has a strong cube texture of 98.7%(<10°) as commercial Ni5W substrate, but overwhelming high yield strength of 310 MPa – twice of Ni5W substrate. Meanwhile, the saturation magnetization of the Ni10W substrate is only 4% of the Ni5W substrate. Furthermore, through the in-situ EBSD tensile observation of the stability of the strip, it is found that the grain orientation and grain boundaries of the substrate present very high stability up to 0.2 % strain, which is beneficial to the roll-to-roll preparation of the coated conductor. A CeO_2 buffer layer was successfully deposited on the super high tungsten substrates, which indicates that the substrates are suitable for REBCO coated conductors. The super high tungsten substrate with strong cube texture, high yield strength and negligible magnetization can significantly improve the progress of using the RABiTS route in the fabrication of REBCO tapes. Meantime, the mechanisms of the cube texture evolution and tungsten diffusion in super high tungsten substrate are also studied.

Keywords: Super high tungsten, Substrates, Coated conductors, Cube texture

WBP8-2

Laser scribing of stacked coated conductors laminated with solder

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We have studied the multi-filamentary structure in the stacked coated conductors(CCs) laminated with solder by laser scribing. When the filament-width is comparably narrow with the size of defects, the defects act as origin of filament-Ic degradation. This is the reason for low yield of scribed tapes. The objective of this study is to reduce the probability of the filament-Ic drop. The laser scribing was performed for the specimens that laminated a normal CC to the artificially defect introduced CC. As a result, it was found that a certain critical current can be obtained even in a filament with defects. This work was supported by NEDO.

Keywords: coated conductors, laser scribing

WBP8-3

Fabrication of $YBa_2Cu_3O_y$ coated conductor by Vapor-Liquid-Solid growth technique using Reel-to-Reel system

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Nagoya university[1]

In fabricating $REBa_2Cu_3O_y$ (REBCO) superconducting coated conductors (CCs), in order to reduce the production cost, it is necessary to increase deposition rate. However, when using PLD method, the crystallinities of the REBCO layer are deteriorated by increasing the deposition rate. From our early studies, by using VLS (Vapor Liquid Solid) growth technique, we found that VLS growth technique was possible to achieve both favorable crystallinities and high deposition rate[1]. However, previous reports on VLS growth technique are using a static system without the substrate transportation during the YBCO film deposition, so it is difficult to prepare long REBCO CCs. In this study, we extended the VLS growth technique for fabricating YBCO CCs by using Reel-to-Reel (RtoR) system with substrate transportation.

REBCO CC using the VLS growth technique consists of three layers of solid layer, liquid layer and vapor layer. When a YBCO CC is fabricated by VLS growth technique using the RtoR system, the liquid layer is solidified since the substrate is away from the heater after the liquid layer deposition. Therefore, we examined whether the solidified liquid layer would be melted by re-approaching to the heater. Fig. 1 shows X-ray diffraction patterns of the VLS-YBCO thin films re-approaching the heater at different transfer-speeds of 1.8 and 3.6 m/h. In the case of 1.8 m/h, no $BaCuO_2$(600) peak appeared due to re-melting the liquid layer. On the other hand, when transfer-speed was 3.6 m/h, there was $BaCuO_2$(600) peak. This fact indicates that the solidified liquid layer is not able to re-melt because the substrate temperature was not able to follow the heater temperature due to the high transfer-speed.

Fig. 2 shows liquid layer thickness dependence of J_c at each solid layer thickness. The total film thickness about 1.8 μm. With reducing the thickness of the solid layer and the liquid layer, we achieved 2.04 MA/cm² at overall deposition rate 17 nm/s. This result indicates that the thin solid layer provided good seed crystal without *a*-axis grains and the reducing liquid layer thickness suppresses melt-back of the seed layer to the liquid layer.

This work was partly supported by JSPS (19K22154), JST-ALCA,JST-A-STEP and Power Academy. The metal substrates were provided from AIST.

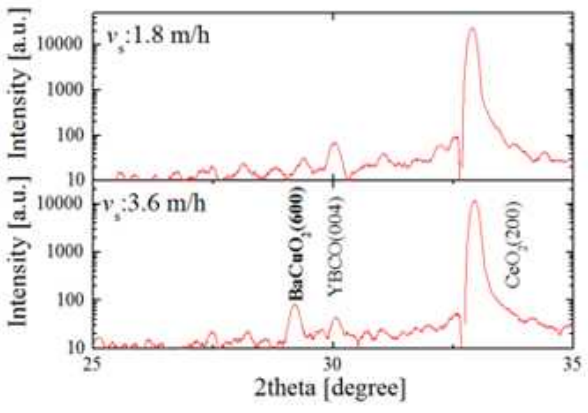

Fig. 1 X-ray diffraction patterns of VLS-YBCO CCs re-approaching to the heater at transfer speeds of 1.8 and 3.6 m/h.

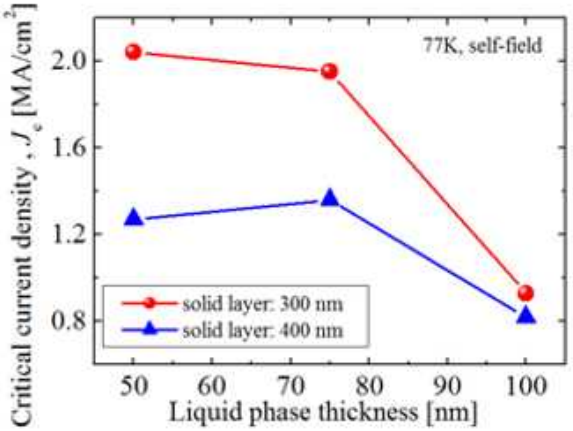

Fig. 2 Liquid layer thickness dependence of J_c at each solid layer thickness.

[1] T. Ito *et al.*: Abstracts of CSSJ conference, Vol.96, p.31 (2018)

Keywords: REBCO, Vapor-Liquid-Solid growth technique, Reel-to-Reel system

WBP8-4

Angular dependence of critical current for REBCO coated conductor under various bending strains

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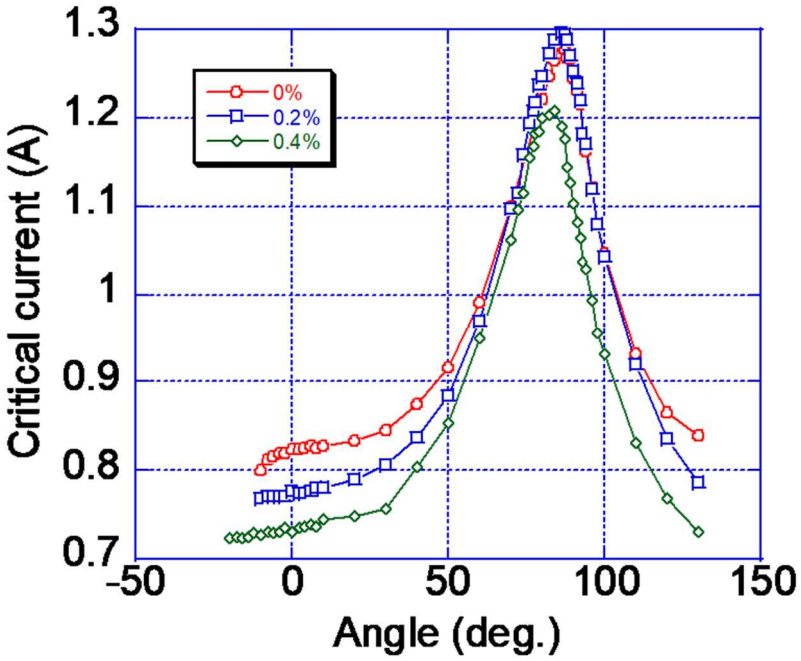
$REBa_2Cu_3O_y$ (REBCO, RE = Y, Gd, Sm, Nd, etc) coated conductors are expected to be applied to high magnetic field superconducting magnets because the conductors have very high mechanical properties and high superconducting properties even in a high magnetic field. In addition, it is well known that the critical current of REBCO coated conductors follows an almost parabolic dependence as a function of axial strain [1]. In this study, we focused on the strain effect of the REBCO. In order to improve critical current of the REBCO coated conductors using the strain effect, the relationship between strain and critical current was investigated. A superconducting properties measurement device in various environment was developed. The device can measure critical current at low temperature, various magnetic field and various field angles under bending strains.

The GdBCO coated conductor, produced by Fujikura, with 0.2 mm micro-bridge was prepared. The angular dependences of critical currents for GdBCO coated conductors under various bending strains are shown in Fig. 1. The critical currents at various magnetic field angles and bending strains were estimated by the new device. We found that the critical current at angle of 90° under 0.2% bending strain has a little enhancement by the strain. This behavior is different from the strain effect at angle of 0°.



Keywords: REBCO, Bending strain, Angular depndence, Critacal Current

WBP8-5

Study on $(Nd_xSr_{1-x})TiO_3$ thin film as conductive buffer layer for low-cost REBCO wire

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To develop low-cost REBCO superconducting wires, we have developed a new architecture using conductive rather than insulating buffer layers, combined with {100}<001> textured pure Cu tape to form $YBa_2Cu_3O_7$/Nb-doped $SrTiO_3$/Ni/Cu/stainless steel tape. In this structure, the textured pure Cu tape is expected to work not only as the template for YBCO biaxial crystal alignment but also as the stabilizing layer. We fabricated YBCO/$Sr(Nb_{0.15}Ti_{0.85})O_3$/Ni/Cu/SUS316 short sample with the J_c of 2.5 MA/cm^2 (at 77 K, self-field), and also confirmed that some current flowed into the Cu tape through the conductive buffer layers when the current exceeded the critical current of the YBCO layer [1]. However, although the resistivity of $Sr(Nb_{0.15}Ti_{0.85})O_3$ was assumed to be approximately (1.2–8.6) × 10^{-3} ohm-cm at 77 K before the YBCO deposition, the resistivity of $Sr(Nb_{0.15}Ti_{0.85})O_3$ layer in the YBCO/$Sr(Nb_{0.15}Ti_{0.85})O_3$/Ni/Cu/SUS316 increased to be few ohm-cm after the YBCO deposition and/or oxygen annealing. Because lower resistivity of the conductive buffer layer is favorable, we tried to suppress the increment of the resistivity during the YBCO deposition and oxygen annealing. In this study, we applied $(Nd_xSr_{1-x})TiO_3$ to the conductive buffer layer instead of $Sr(Nb_{0.15}Ti_{0.85})O_3$.
The electrical resistivity of the as-grown $(Nd_{0.1}Sr_{0.9})TiO_3$ thin film prepared on $LaAlO_3$ single crystal substrate by a PLD method was 4.55×10^{-2} ohm-cm at 77 K. $(Nd_xSr_{1-x})TiO_3$ and YBCO layers were prepared by a PLD method on the Ni-electroplated Cu/SUS316 tape. Fig.1 (a) and (b) show X-ray {110} pole figure and SEM image of the $(Nd_{0.1}Sr_{0.9})TiO_3$ thin film prepared on the Ni/Cu/SUS316. We can see that the $(Nd_{0.1}Sr_{0.9})TiO_3$ film had excellent biaxially crystal orientation and smooth surface. Fig. 1 (c) shows X-ray (102) pole figure of the YBCO prepared on the $(Nd_{0.1}Sr_{0.9})TiO_3$/Ni/Cu/SUS316. We confirmed that the YBCO also had excellent biaxially crystal alignment.
A part of this work was supported by JST ALCA Grant Number JPMJAL1109, Japan.

[1] Doi et al., appl. Phys. Express 12 (2019) 023010.

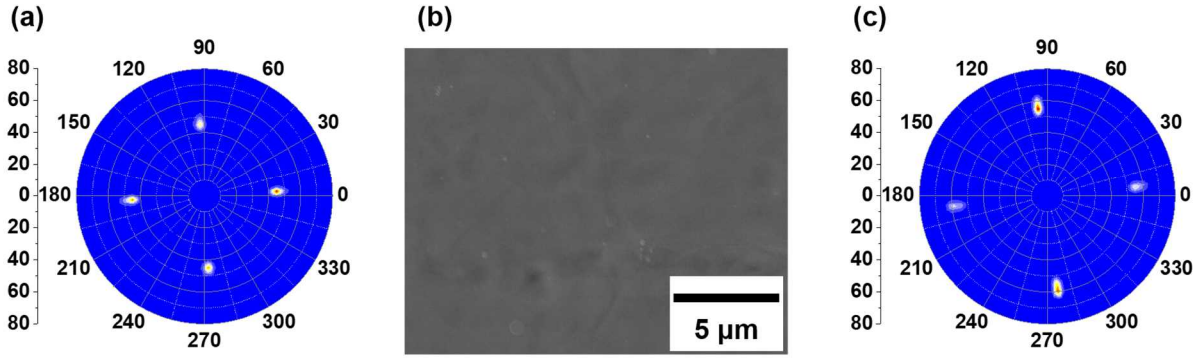

Fig.1(a) X-ray {110} pole figure and (b) SEM image of the $(Nd_{0.1}Sr_{0.9})TiO_3$ prepared on the Ni/Cu/SUS, and (c) X-ray (102) pole figure of the YBCO prepared on the $(Nd_{0.1}Sr_{0.9})TiO_3$/Ni/Cu/SUS.

Keywords: conductive buffer layer

WBP8-6

Influence of Different Narrowing Methods on Critical Current of 1 mm HTS Tapes

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Over the past decade, a great progress has been achieved in terms of performances of high temperature superconducting (HTS) tapes, such as the critical current of the tape with 4 mm width exceeds 200 A. Due to the high critical current, the narrowing process to 1 mm width for the HTS tape became a feasible technology, and the value of critical current for the 1 mm tape is able to above 50 A. The 1 mm width tape is firstly suggested by our group in 2016, and a soldered-stacked-square (3S) wire is also fabricated based on the 1 mm tape. However, during the narrowing process, some loss of critical current was observed in many experiments. This significantly affects the stable fabrication of the 3S wire. To understand the influence of narrowing process on critical current, we proposed two narrowing methods to manufacture the 1 mm tapes, mechanical cutting and laser cutting methods in this paper. Meanwhile, the soldering tin plating process is also considered in the manufacturing process of 1 mm tape. The critical current measurements were carried out in order to make a comparison with these two methods. The detailed results about the critical current measurement experiment, the microscope observation experiment, and the soldering tin plating process are presented and discussed in this study.

WBP8-7

Effect of extra addition of Ba into $YBa_2Cu_3O_{7-\delta}$ coated conductor with $BaHfO_3$

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Critical current density (J_c) of $YBa_2Cu_3O_{7-\delta}$ (YBCO) film in magnetic fields can be enhanced by introducing $BaHfO_3$ (BHO) flux pinning centers into the film [1]. In order to increase J_c, the YBCO films are fabricated by a metal organic deposition method using chemical solution with Ba deficient composition [2]. In this case, about 1 μm sized CuO precipitates were formed on the film surface due to the Ba deficient in our previous study [3]. In this study, we added extra Ba into the starting solution to compensate the shortage of Ba and investigated the influences of this Ba addition on the surface morphology.

Starting solution contains elements of Y, Ba, and Cu with molar ratio of 1 : 1.5 : 3. Two types of solution were prepared using the starting solution; one is added Hf of 10 mol% (indexed as Hf10), and another one is added both Hf and Ba of 10 mol% (indexed as Hf10-Ba10). These two solutions were spin-coated onto CeO_2/$LaMnO_3$/MgO/$Gd_2Zr_2O_7$/Hastelloy substrates separately, then the coated films were calcined to prepare precursor films at 430 °C in O_2 gas flow. Finally, the precursor films were crystallized to prepare YBCO at 780 °C in mixed gas flow of Ar and O_2. Surface morphology and elemental mapping of the samples were observed by a scanning electron microscopy (SEM) and an energy dispersive X-ray spectroscopy (EDS).

Fig. 1 shows SEM images and EDS elemental distribution maps of Cu and O for the samples prepared from each solution. CuO precipitates were observed on the sample surface in both films, whose sizes were almost the same. Table 1 shows the comparison of number density of CuO precipitates seen in Fig. 1 for each sample. CuO precipitates of Hf10-Ba10 decreased by about 60% compared to Hf10. It is suggested that extra addition of Ba is effective to suppress the formation of CuO.

[1] S. Engel et al Appl. Phys. Lett. 90 (2007) 102505
[2] K. Nakaoka et al Physica C 463 (2007) 519-522
[3] S. Yamada et al ISMMM Program Book (2018) 44

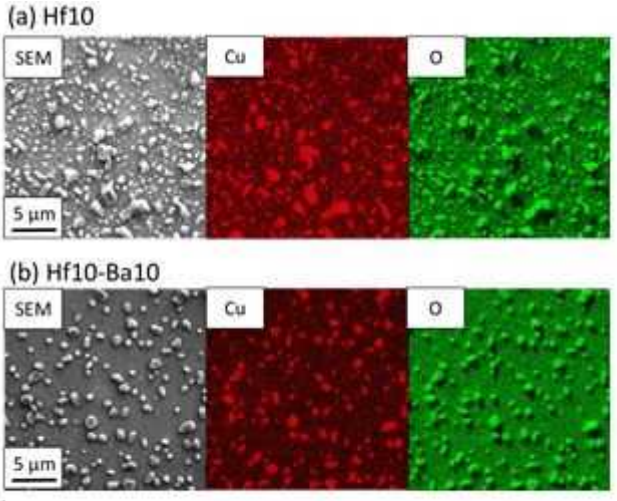

Table 1 Comparison of number density

	Number density (cm^{-2})
(a) Hf10	1.75×10^6
(b) Hf10-Ba10	6.77×10^5

Fig. 1 SEM images and EDS mappings of sample surface.

Keywords: YBa2Cu3O7-δ , BaHfO3, Flux pinning center, Extra addition of Ba

WBP8-8

Development of artificial cracked RE123-coated conductor for realizing compatibility of critical current improvement and diamagnetism reduction

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Muroran Institute of Technology[1]

The filamentation of tape shaped RE123-coated conductors is important to reduce the shielding current and Ac loss in the wire and coil, but the critical current is usually decreased [1]. To increase the critical current, a method is artificial pin doping, however, it is ineffective on reducing of the shielding current or AC loss. Realizing compatibility of critical current improvement and AC loss reduction is important to develop a high field magnet and highly-efficient AC devices. To achieve both, we suggested an artificial cracked RE123-coated conductor. In last year, we reported the development of split wire with 16-main-core by electrical separating by bending stress (ESBS) method [2]. In this study, the wire was fabricated with tear stress along width direction of the wire, then the cracks were formed along longitudinal direction of wire. In experiments, several samples were prepared, and the critical current was increased 14% than the original wire at 0.7 T, with great decreases of diamagnetism (shielding current). The fabrication method and the results will be discussed in upcoming ISS2019 at Kyoto.

[1] Xinzhe Jin, Hidetoshi Oguro, Yugo Oshima, Tetsuro Matsuda and Hideaki Maeda, "Development of a $REBa_2Cu_3O_{7-\delta}$ multi-core superconductor with “inner split” technology," Superconductor Science and Technology **29** (2016) 045006 (8pp)
[2] Xinzhe Jin, Yasuteru Mawatari, Toshihiro Kuzuya, Yusuke Amakai, Yoshinori Tayu, Naoki Momono, Shinji Hirai, Yoshinori Yanagisawa, Hideaki Maeda, "Fabrication of 16-main-core RE123 split wire using inner split method," IEEE Transactions on Applied Superconductivity **29** (2019) 6601304 (4pp)

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This work was supported by the MEXT project of Leading Initiative for Excellent Young Researchers (LEADER) in Japan (Project ID: 16810210).

Keywords: RE123, coated conductor, superconducting wire

WBP9-1

Study of hetero junction between RE123 and Bi2223 tapes with JIM method

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In this study we studied to develop a superconducting joint between RE123 and Bi2223 as hetero junction. This type of joint is called as RB joint. The fabrication method for the RB joint is JIM [1]. The joint is useful to develop a high-field RE123/Bi2223 persistent magnet, also it is useful to joint between RE123-coated conductors and between Bi2223 wires, as RBR and BRB, respectively. In the heat treatment for joint, Bi2223 phase is melted and the RE123 keeps the crystal orientations. In experiment, several samples were prepared and all samples show a superconducting behavior at 77 K. The fabrication method and properties of resistance for the RB joints will be presented in ISS2019.

[1] X. Jin, et al., Superconductor Science and Technology 32 (2019) 035011.

Acknowledgements:
This work was supported by MEXT project of Leading Initiative for Excellent Young Researchers (LEADER) Project ID 16810210, and JSPS KAKENHI Grant Number JP18K04719, Japan.

Keywords: joint, Bi2223, RE123

WBP9-3

Superconducting Joints of *In Situ* PIT and IMD Processed MgB_2 Conductors

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Superconducting joints are essential to use magnesium diboride (MgB_2) conductors in liquid helium (LHe)-free magnetic resonance imaging (MRI) magnet system operated in a persistent mode by forming a closed-loop using superconducting joints. *In situ* PIT (powder-in-tube) processed multifilament MgB_2 conductors are known to have good potential to use in LHe-free MRI magnet. However, internal magnesium diffusion (IMD) processed MgB_2 conductors show superior performance compared with *in situ* PIT processed MgB_2 conductors. Therefore, if high current capacity joints using IMD conductors can be fabricated, it will be certainly advantageous. We have fabricated superconducting joints using unreacted multifilament (18 + 1) *in situ* PIT and monofilament IMD processed MgB_2 conductors and evaluated their performance in different temperatures up to 25 K and magnetic fields up to 12 T. Our joints fabricated using 18 + 1 filaments *in situ* PIT and monofilament IMD processed conductors attained critical current of 121.7 A at 10 K in 0.5 T and 128.6 A at 20 K in 1 T, respectively. The current retention in the joint fabricated using IMD processed conductors in compared with the bare wire was close to 100% at 20 K in the field range from 7 T to 2 T. The joint resistances evaluated using the field-decay measurement by forming a closed-loop of the *in situ* PIT and IMD processed conductors were 5.16×10^{-15} Ω and 2.01×10^{-13} Ω at 20 K in self-field, respectively. The detailed joint fabrication process, transport measurement results, microscopy analysis of the joint part, and the field-decay measurement results of both types of joints will be presented.

Keywords: Magnesium Diboride (MgB2), Magnetic Resonance Imaging (MRI), Superconducting Joints

WBP9-4

The development of superconducting joint technologies for MgB_2 wires

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National Institute for Materials Science[1]

Magnesium diboride (MgB_2) has a high critical temperature (T_c = 39 K) as a metal-based superconductor and one of candidate materials for superconducting application operated free from liquid helium. The superconducting joint between MgB_2 wires is an important technique in consideration of applications such as MRI magnet. We have been developing an internal magnesium diffusion method (IMD) wire with high critical current density J_c, and succeeded in developing a good superconducting joint for unreacted wires, and its joint resistance is 10^{-13} Ω. On the other hand, the superconducting joint of the reacted wire has many unsolved problems. In this research, the superconducting properties and the microstructures about the influence in the second heat treatment for fabricating of superconducting joint part.

We prepared unreacted 19-multifilaments wire made by Hypertech Research Inc. of the United States. These wires heat treated in a tube furnace under an argon atmosphere at 650 °C for 1 hour. Furthermore, the same heat treatment was performed again on the same sample to evaluate the superconducting properties like making a superconducting joint. We have been used a FIB-SEM for understanding the microstructures the obtained image was constructed as a three-dimensional image.

Fig.1 shows the results of the magnetic field dependence of J_c of single heat treatment and dual heat treatment. It was found that J_c of single heat treatment was improved in the entire magnetic field region in the two-time heat-treated wire. As a result of the 3-D microstructural observation, as shown in Fig. 2, a filament containing a large amount of unreacted Mg could be observed in a single heat treatment (a), but those filaments were reduced in a dual heat treatment wires.

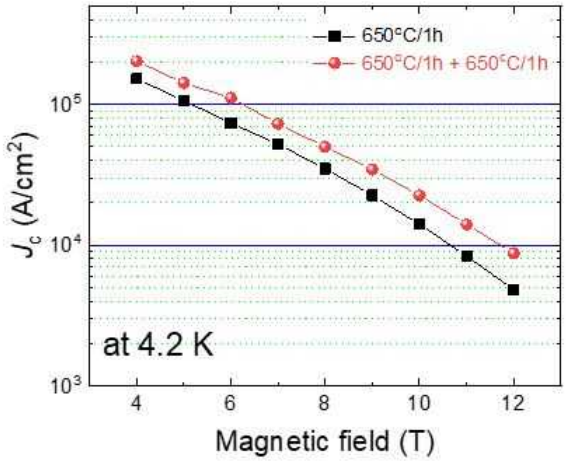

Fig. 1. Magnetic field dependence of critical current density at 4.2 K for single and dual

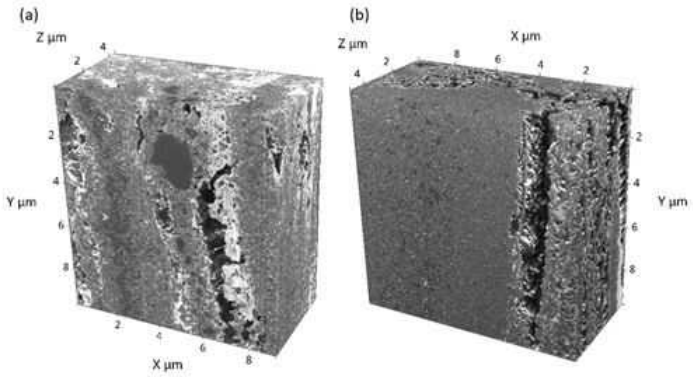

Fig. 2. 3D-microstructure inside filament after (a) heat treatment single and (b) dual.

Keywords: MgB2, Superconducting joint, 3D images, multifilament

WBP9-5

Superconducting Joint Between $Ba_{1-x}K_xFe_2As_2$ Tapes by Using a Cold-press Technique

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Significant progresses toward high performance iron-based superconducting wires/tapes have been made over recent years [1]. Especially for $(Ba,K)Fe_2As_2$, the critical current density exceeded 1.5×10^5 A/cm^2 at 4.2 K under 10 T [2]. For the practical use, a superconducting joining technique is of critical importance. Recently, Zhu *et al.* reported that the superconducting joints fabricated via a hot press (HP) technique show a critical current ratio (CCR) of 63 % at 4.2 K under 10 T. [3] Although the achieved high CCR demonstrates the high potentiality of iron-based superconductors, the CCR value has not been obtained without the HP process unfavorable for industry. Thus, it is necessary to achieve high CCR using a simple process.

In this study, we fabricated superconducting joints between $(Ba,K)Fe_2As_2$- tapes by using a simple cold uniaxial press technique and evaluated their performance. Figure.1(a) shows critical currents (I_c) and CCR of the joint at 4.2 K under magnetic fields parallel to the tape surface. CCR values of 63 % in the self-field and 29 % in 3.5 T at 4.2 K were achieved. Figure. 1(b) shows a SEM image of the cross section of the joint. Micro-cracks were not observed around the jointed part, which is well connected. On the other hand, as shown in Figure. 1 (c), inhomogeneous deformation and macro-cracks were observed at the joint end part. These results suggest that joint end parts prevent CCR from increasing to more than 63%.

[1] Yao. C *et al.*, Supercond. Sci. Technol. **32**, 023002 (2019).
[2] Huang. H *et al.*, Supercond. Sci. Technol., **31**, 015017 (2018).
[3] Zhu. Y *et al.*, Supercond. Sci. Technol., **32**, 024002 (2019)

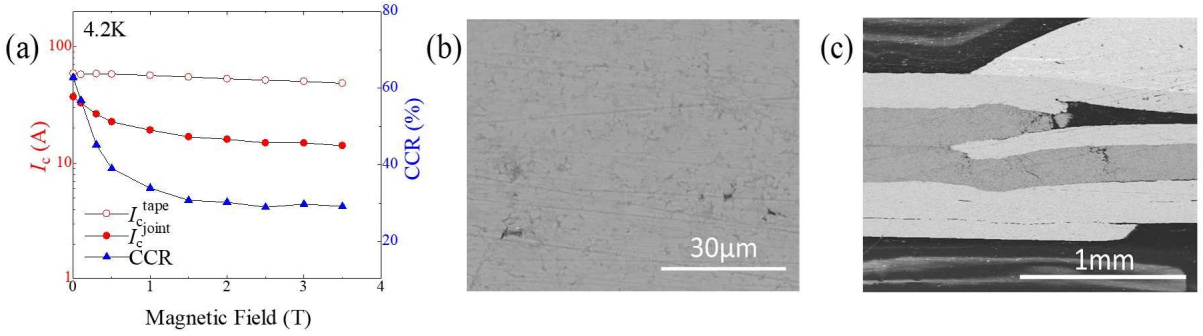

Figure. 1: (a) Magnetic field dependence of I_c and CCR of $(Ba,K)Fe_2As_2$ tape and joint at 4.2 K under field parallel to the tape surface. SEM images of (b) the cross section and (c) the end part of $(Ba,K)Fe_2As_2$ joints.

Keywords: Iron-based superconductors, Superconducting joint, Critical Current Ratio, Critical current

WBP9-6

Fabrication of additional deposited layer of $GdBa_2Cu_3O_{7-\delta}$ on coated conductors for joint

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National Institute For Materials Science, Japan[4]

$REBa_2Cu_3O_{7-\delta}$ coated conductors (REBCO CCs) have been longed for electric power application with lengthening by superconducting joint due to its high critical temperature (T_c), critical current (I_c), and low toxicity[(1)(2)]. We have reported jointing GdBCO CCs via crystallization of additional deposited precursor layers on GdBCO CC[(3)], and which showed I_c of 0.096 A/cm[2(4)], however that is lower than that of 10^3 A/cm^2 in YBCO c-axis[(5)]. Existence of secondary phases and voids at joint interface would deteriorate current and formation of them are affected by the structure of additional layer after film growth. In this study, surface morphology of additional layer were observed to clarify the information of microstructure.

Additional layers were fabricated by a metal organic deposition[(3)] method. Firstly, starting solutions were spin-coated onto GdBCO CCs, and the samples were calcined at 823 K. Next, they were heated at 1073 K under the oxygen pressure of 200 Pa to crystallize and oxygenated at 773 K for 2 hours. Then the film surface was observed by a Scanning Electron Microscopy (SEM). Fig.1 show SEM images of film surface of GdBCO layer before (a) and after (b) additional deposition onto GdBCO CC. The contrast difference is small in whole area in Fig.1 (a), showing smoothness. On the other hand, the contrast difference is large in Fig.1(b), showing roughness. In addition, the number of grains is large in Fig.1(b), which indicates the roughness is due to the existence of many grains. The roughness of film surface may cause voids at the joint interface of the jointed sample. It is necessary to fabricate additional layer with smooth surface to increase I_c, so improving heat treatment conditions is needed.

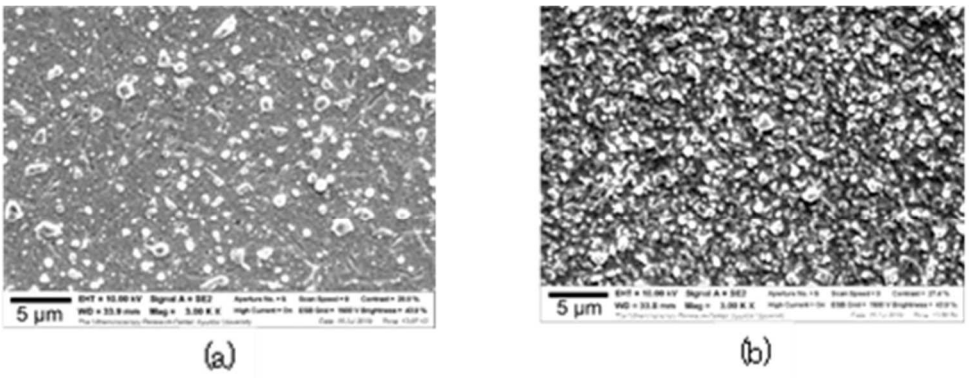

Fig.1 SEM images of film surface of GdBCO layer before (a) and after (b) additional deposition onto GdBCO CC

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