INTERNATIONAL WORKSHOP ON

Construction of Low-Carbon Society Using Superconducting and Cryogenics Technology

March 7-9, 2016

Cosmo Square Hotel & Congress, Osaka Japan
In recent years, smart grid concept is acquiring great interest because smart grid could accept more renewable energy into power system to control power system equipment precisely by IT technologies. Even in smart grid concept, advancement of fundamental generation, transmission, and energy storage is very important to increase power system efficiency, and also to decrease CO\textsubscript{2} emission, as IT technologies could only control power flow and sometimes save a waste of electricity.

To reduce power loss of transmission, superconducting technologies will be very effective as it is essentially no resistance up to critical current level. Even in ac current, it is possible to reduce transmission loss including cryogenic cooling power consumption by adequate design of power cable configuration. In the case of dc power transmission, superconductivity will show more possibility to reduce transmission loss, including power transmission from off shore wind power to landing point.

Power conversion from dc to ac is also a key technology to increase system efficiency of renewal energy, like full conversion type wind power generation or solar panel generation. Recently, SiC power device including switching function has been developing rapidly, and start to show its abilities to increasing power system efficiency.

To connect as much of distributed renewal energy to power system, high flexibility of power generation control is desirable. One example is second battery energy storage and other one is fast responding gas turbine generation system. In many second battery energy storage technologies, Li Ion second battery technology is showing rather high storage efficiency. As fast responding gas turbine has already realized as jet engines for air craft, research and development is still needed to realize long life time and high generation efficiency. Energy storage technologies and fast responding generation technologies might be conflicting with each other in one power system, as both technologies will be installed to accept fast generation power change of renewable generation. To compare merit and demerit of both technologies including generation cost, each technology must be developed well to provide correct technical information for comparison.

Over view of these topics will be reviewed in my talk.
Novel HTS SMES Applications to Achieve Higher Energy Efficiency and Prospective Energy Saving for CO₂ Reduction

Prof. Jian Xun Jin
School of Electrical Engineering and Automation, Tianjin University, China

The applied high temperature superconducting (HTS) materials and technologies have been well enabled to build various applicable devices especially electric power devices which technologies have been well verified to be industrialized for future practical applications. Their industrial applications with unique characteristic and novel methodology have potential to dramatically increase power system efficiency and energy saving, and consequently reduce carbon emission with environmental friendly architectures.

Superconducting magnetic energy storage (SMES) device has a wide range of applications with various novel utilizations, as an example it can be utilized to form a high efficient power grid, such as a sample low-voltage rated DC power transmission network integrated with superconducting cables (SCs) and SMES devices. In addition to the SC properties of loss-less and high current transportation capacity, the effectively integrated system has a self-acting fault current limitation (FCL) feature of the SC and a buffering effect of the SMES to power fluctuations. The integrated system can achieve high-quality power transmission under common power fluctuation conditions with an advanced self-protection feature under short circuit conditions, which novel and smart system is identified to suit especially the smart grid applications. Further investigation example includes grounding fault protection characteristics in a novel low-voltage DC power transmission, distribution, and utilization network integrated with multiple FCLs, SCs and SMES devices. The effectively integrated system is highlighted with a fast-response grid voltage protection feature of the SMES. The cooperative operations of the FCL SC and the SMES are favorable for achieving advanced fault current limitation, fault-ride-through capability enhancement, critical load protection during a grounding fault, and effective energy management with higher system efficiency.

Energy conservation and emission reduction becomes a critical task for the present power system. The applied superconductivity as innovative technology is with great potential to incorporate. With regard to energy losses and carbon emissions in the electric power system, the potential benefits of various HTS power applications and features related to energy conservation and emission reduction are explored and verified with the consideration of extensive direct and indirect benefits for energy saving and efficiency improvement in the future power systems.
Development of a long-length direct current transmission system
with high-Tc superconducting cable for future low-carbon societies

Noriko Chikumoto and Satarou Yamaguchi
Chubu University

High temperature superconducting (HTS) power transmission systems attract much attention because they are expected to achieve large power capacity and low transmission energy loss. In particular, if it is used in the DC power transmission system, we can have a largest advantage of superconductivity, not only because of the almost zero joule heating, but also because it is free from AC loss which is unavoidable technical difficulty for superconductor in AC application. Other advantage of DC power transmission is it is more suitable for the power transmission from various renewable sources, such as wind, solar photovoltaic power, etc., because they produce either variable frequency AC or inherently DC electric power.

Hence, we have started the development of DC power transmission system on 2006. Firstly we have started with a 20-m cable system, then it was enlarged to a 200-m system. Then in FY2013, a new national project to construct and verify the superconducting DC power transmission line with total length of 1.5 km was launched in the Ishikari area. The objective of the national project, so-called ‘Ishikari project’, is to design a system and verify the safety and validity for a practical use, and also to obtain the properties required to get a future prospect for longer length cable system. There, two power lines have been installed. “Line 1” connects a photovoltaic power plant (PV) and an internet data center (iDC) by a 500-m underground superconducting cable system (5kA, 100MVA) for practical use, while “line 2” with 1000-meter cable (2.5 kA, 50MVA) will be used for verification tests. The construction was started in the field in June, 2014 and completed at the end of April, 2015 for “line 1”. Then we performed the first cooling test for “line 1” from May to June, 2015, followed by the second cooling test from the end of August to October, 2015. On the other hand, the system design of the line 2 started from April, 2013, the construction in the field was started from Oct., 2014 and it was completed by the end of Oct., 2015. Then we performed the evaluation test of the cooling system from Nov, 2015 for about one month.

In the workshop, we will over view the development and the result of the cooling tests for above systems, then we will discuss about the efficacy of the superconducting DC cable system for reduction of carbon emission.

This work is in part supported by the Japanese Ministry of Economy, Trade and Industry (METI), and a grant from the Strategic Research Foundation Grant-aided Project for Private Universities, Ministry of Education, Culture, Sports, Science and Technology (CAST). The authors acknowledge the H. Watanabe, Y. V. Ivanov, H. Takano, M. Hamabe, N. Inoue, A. Iiyoshi in Chubu University and all members of the R&D partnership of Ishikari Superconducting DC Power Transmission System (i-spot).
The possibility of HTS wind power generator for the future of eco-friendly society

Minwon Park

Recently, gearless type wind power generators, which have very low rotation speed and high torque, have been preferred over the geared type due to the gearbox reliability. Because the gearless generator becomes very large and heavy, many companies have tried to develop a wind power generator with larger capacity, smaller size and lighter weight. A high-temperature superconducting (HTS) generators could be a key technology used to achieve these issues. Therefore, the HTS generator draws much attention from large-scale offshore wind power generation systems. It has nevertheless limitations to be manufactured due to some drawbacks. The high cost of HTS wires is regarded as the biggest obstacle to the commercialization of the HTS generator.

This paper deals with the possibility of HTS wind power generator for the future of eco-friendly society. The costs of the 12 MW HTS generator is estimated considering key factors like the weights of the materials, supporting structure and losses of generator. The marginal critical current density of the HTS wire is examined to minimize the total cost of wind power generation system with HTS generator. Then a 12 MW HTS generator using the estimated HTS wire that has reasonable critical current density is newly designed, and the magnetic field distribution of the HTS generator is analyzed using 3D finite element method.

Based on the results, the electromagnetic and mechanical performances of the 2G HTS wire were discussed including high magnetic field, torque and force of the generator. Finally, a reasonable price of the 2G HTS wire for commercialization of the HTS generator was also suggested. The designed 12 MW HTS generator using the estimated HTS wire can effectively be utilized to develop large-scale wind power generation systems.
Low Carbon Emission Drive Motor System for Next Generation Transportation Equipment- Current Status and Future Perspective

T. Nakamura (Kyoto University)

Our R&D group has been developing next generation drive motor for the next generation transportation equipments, e.g., train, bus, automobile. Our target motor is called High Temperature Superconducting Induction/Synchronous Motor (HTS-ISM). Although basic structure of the HTS-ISM is the same as that of the squirrel-cage induction motor, prominent performances such as highly efficient synchronous rotation mode is possible with the use of the HTS rotor windings. We have already developed a 20 kW class prototype motor, which is cooled by liquid nitrogen (77 K). We have shown, based on the test and the analysis, the prominent characteristics, e.g., high efficiency for different drive speed and for regeneration mode, overload slip rotation at 41.3 kW, fast acceleration with overload (less than 1 s), successful variable speed control with so-called JC08 mode. Also, we have been developing a high efficiency cryocooler and low thermal invasion cryogenic structure.

Furthermore, we are going to develop an HTS stator windings, i.e., fully HTS-ISM, and then are realizing both of ultimate high efficiency against the variable speed control and high torque density at low speed. Especially, we can remove so-called transmission gears, of which are heavy in weight and generate much losses, (direct-drive system), by utilizing the high torque performance. Finally, we are aiming at low carbon emission drive motor system that can overcome the conventional (normal conducting) motor, even we consider the power consumption of the cryocooler. Detailed results will be presented, and future perspective is also to be discussed.

Acknowledgments
This work has been supported by Japan Science and Technology Agency under the program of Advanced Low Carbon Technology Research and Development Program (JST-ALCA) in Japan.
Present status and future trends of R&D for superconducting rotational machines in Japan
Osami Tsukamoto (Sophia University)

Abstract
Various HTS rotating machines, from large scale of MW class to small scale of kW class, are being developed in Japan. R&D statuses of those machines and future trends of HTS rotational machines technologies are presented in the paper. Design and feasibility studies of HTS wind power generators are conducted in Japan and those designs are presented and their merits and demerits are reviewed. In addition to those reviews some technical issues on HTS field coils to realize practical machines, stability / quench protection and robustness of HTS field coils, are also studied.
Superconducting magnet technology, a promising way to reduce industrial emissions and pollutions in China

Laifeng Li

Technical Institute of Physics and Chemistry, Chinese Academy of Sciences, Beijing

Global warming has become serious due to greenhouse-gas emissions. Faced with this situation, Chinese government has committed to cut the carbon dioxide emission per unit of gross domestic product by 40%-45% by 2020 from the 2005 level of 7.467 billion tons of CO₂ equivalent.

A large source of greenhouse-gas emissions comes from wastewater treatment industry. In traditional activated sludge method, organic contaminants are degraded into CO₂ and water under aerobic conditions, or transformed to methane under anaerobic conditions. The thickening and burning of sludge can also produce a large amount of CO₂.

Compared with traditional chemical and biological wastewater treatment methods, superconducting magnetic separation (SMS) aimed to be used in wastewater treatment increasingly attracts attention, which is a physical and environmental friendly method without greenhouse-gas emissions. In 1987, fundamental researches of SMS method in wastewater treatment were started in Osaka University. The first cryocooler cooled SMS wastewater treatment system was established by Prof. Nishijima in Osaka University and they succeeded in practical use such as the water purification of paper mill. Since 2004, we have collaborated with Prof. Nishijima, and brought this concept into China.

In this presentation, the development of magnetic separation technology for water purification in China will be introduced in details, including permanent magnet, superconducting magnet, new magnetic seeding materials, collaborative research activities with Osaka University and sino-companies as well as some practical application examples in China. The relationship between SMS technique and emission reductions will be also discussed.
On-Site Soil Washing Technology Using Magnetic Separation for Treatment of Metals-Contaminated Soil

Keijirou ITOH, Kajima Corporation

Japanese Soil Contamination Countermeasures Act was enforced in 2003, and initially the Act was limited to anthropogenic contaminated soil. But, under 2010 amended Act, naturally occurring heavy metal contamination has been included. So we need to remove heavy metals from contaminated soil on-site at low cost more than ever before. From such a background we have developed new washing technology using magnetic separation for treatment of metals-contaminated soil and have achieved two applications on-site. This technology led to resource saving and reduction of carbon dioxide, because the contaminated soil in the site was remediated on-site and used as backfill material.

The contents of my presentation are as follows:

1. Japanese social background about contaminated soil
2. New soil washing technology
   - Iron powder adsorption of heavy metals
   - Superconducting magnetic separation
3. Application example A
   Anthropogenic contaminated soil of lead and arsenic
4. Application example B
   Naturally occurring contaminated soil of arsenic in tunnel construction
Iron Oxide Scale Removal from Boiler Feed-Water in Thermal Power Plant by Magnetic Separation

Shigehiro NISHIJIMA, Osaka University

To decrease the carbon dioxide emission from thermal plants, we proposed a water treatment system with superconducting High Gradient Magnetic Separation (HGMS) which is applicable in the high-temperature and high-pressure boiler feed water.

Recently, reduction of carbon dioxide emission has been required due to the global warming. It is necessary to keep the efficiency of thermal power plants high because they account for the most of CO\(_2\) emission accompanied with the electric power generation. Main factor of deterioration in the efficiency is the adhesion of the scale such as corrosion products to the pipe wall in feed-water system. Thermal plants have employed All Volatile Treatment (AVT) or Combined Water Treatment (CWT) to prevent scale formation, though these treatments do not prevent scale adhesion completely. 70 µm scale decreases 0.8 % of the efficiency of thermal power plants. The effective method for scale removal has been required for decrease the CO\(_2\) emission.

In low-temperature area of feed-water system the scale exists as the form of iron ion or iron hydroxide. On the other hand the main components of the scale in high-temperature area are magnetite (Fe\(_3\)O\(_4\)) and hematite (α-Fe\(_2\)O\(_3\)), whose magnetic susceptibility and amounts are larger than that in low-temperature area. Therefore, magnetic separation in high-temperature area is effective for removing the scale from feed-water. We proposed a HGMS system that can be operated in high temperature area of feed-water system. In the developed HGMS the ferromagnetic filters are installed in flow channel and magnetized by external magnetic field generated by superconducting magnet. It is required for the system to process 400~500 m\(^3\)/h feed-water and hence we employed superconducting magnet for the large high field area.

First, the scale formed under the high-temperature area of thermal plant was analyzed for the components. It is important to reveal the composition of the scale for highly efficient magnetic separation. Next, the magnetic separation of iron oxide particles under high-temperature (200 °C) and high-pressure (20 atm) condition was conducted and was found more than 98% of separation rate was realized. The result showed the HGMS under high pressure and high temperature was possible for thermal plant. Then the magnetic separation experiment at 353 K and 1150 L/h with superconducting magnet (maximum magnetic flux density, 6 T) for boiler system in a factory was conducted and we confirmed possibility of practical use of developed HGMS system.

**Acknowledgment**

This research was partly supported by “Advanced Low Carbon Technology Research and Development Program (ALCA)” of Japan Science and Technology Agency (JST).
Superconducting technology for Wind-powered Thermal Energy System to realize economic base load power

Toru Okazaki, Ph.D.
Director, International Superconductivity Technology Center (ISTEC)

Wind-powered Thermal Energy System (WTES) is a novel simple idea to realize the economic base load power source. The configuration is shown in figure 1, which is written by DLR. The rotating energy of the wind turbine is converted to the thermal energy by the heat generator, which employs induction heating. The produced thermal energy is stabilized by the thermal energy storage, which costs 1/20 to 1/100 of the batteries. The thermal energy is converted to the electricity by conventional turbine generator, which has about a half efficiency of the batteries. No one has never considered this system because of this low efficient process. However, stabilization is more important than the efficiency.

This low efficiency of thermal to electrical conversion can be improved by making the operation temperature high. The operation temperature is restricted under Curie temperature in the case of the normal conducting system. The superconducting magnet can make strong magnetic field even if the materials lost their magnetic properties at the high temperature. The superconductivity is essential, therefore, to realize high temperature, i.e., high efficiency.

Thermal energy storage utilizes temperature difference. This higher temperature also realizes higher energy density in the same storage material. These merits can be employed from sub-MW wind turbine, which forms wind farms of 20MW in total capacity.

Figure 1. Basic Concept of Wind-powered Thermal Energy System
Development of test device for metal melting by electromagnetic induction heating using superconducting coil

Satoshi FUKUI
Niigata University

In an industrial aluminum casting technology such as production of automotive parts, high efficient and high speed melting technology is required. Metal melting by induction heating using HTS coils is one of candidates.

In this study, we firstly try to verify the capability of induction heating using DC superconductor coils for metal melting in the casting process. We performed a metal melting experiment with the small examination equipment in a magnetic field. The small examination equipment consists of a motor, a heat insulation structure, a rotating shaft, a specimen holder, a frame and the others. About 0.77 kg aluminum pipe; outer diameter was 180 mm and inner diameter was 170 mm, was put into the examination equipment and applied a DC magnetic field from about 1 T at the nearest point to 0.4 T at the furthest point from the magnet. The temperature of aluminum exceeded 500 cent degree within 2 minutes by the rotating at 800 rpm. The melted aluminum in the sample holder was observed after the rotation of 1,200 rpm in 90 seconds, and some amounts of melted aluminum rose over the sample holder outside by centrifugal force. These results indicate that the induction heating with the superconductor coils can supply melting metal of required amount in a short time.

Next, the test device for metal melting by the induction heating using HTS coils was designed using the numerical electromagnetic and thermal analysis. Based on the numerical result, the 1/5 scale test device using YBCO HTS coils was designed and fabricated. In the presentation, the results of the preliminary experiment and the design and fabrication process of the test device is reported.
Study on a high efficiency thermoacoustic engine

Esmatullah Maiwand Sharify, Shinya Hasegawa

Department of Prime Mover Engineering, Tokai University, Kanagawa 259-1292, Japan

Recently, the use of renewable energies has become a major concern for the world energy policy for decreasing the global warming. Therefore, the waste heat recovery and utilizing low grade heat sources for useful work has been an interesting concept to many researchers.

Thermoacoustic is a green technology, which can be used into any application involving heating, cooling and electricity production. Thermoacoustic devices have the potential to take work out of multiple heat sources such as a combination of industrial-waste heat and solar energy. A thermoacoustic engine is an energy-conversion device which converts heat and acoustic power, working either as a heat pump or a prime mover[1]. The thermoacoustic engines are efficient due to the absence of moving parts and relative simplicity of the components. The low manufacturing and maintenance costs make these systems an attractive alternative for clean and effective energy generation. Therefore, the development of a thermoacoustic engines is extremely important for many practical applications.

In this study, we have designed and built thermoacoustic engines and performed experimentally and theoretically investigations. The overall objective is the further progress in the development of the thermoacoustic engines with high efficiency, and we hope that our results would make an important contribution to the advancement of the thermoacoustic field.

Fig. 1. Thermoacoustic refrigerator operating by waste heat of a boat

Current Status and Prospect of Liquid Hydrogen Utilization
Atsushi Shigemori, Iwatani Corporation

Core business of Iwatani Corporation is supply of gas and energy. Hydrogen, previously used as industrial gas, is expected to be used as new energy resource. Since it matches the concept of our core business, we will take proactive stance for expanding the use of hydrogen. Hydrogen has low energy density per unit volume, so transporting and storing large amount of hydrogen gas is necessary. For advancing transporting and storing efficiency, Iwatani promotes liquid hydrogen supplying system.

Iwatani is also focusing on the construction of hydrogen refueling stations since it is an essential element for popularization of fuel cell vehicles to lead the hydrogen energy society. Total of 20 hydrogen refueling stations are planned to be constructed by the end of this fiscal year. Iwatani promotes liquid hydrogen storage type hydrogen refueling station since it is advantageous in terms of transport and storage efficiency. Furthermore, we are working on the development of the cryo-pump system as the next generation of hydrogen refueling station. With the use of cryo-pump, the compression efficiency of hydrogen will be greatly improved.

Iwatani has established Research and Development Center in Amagasaki-city of Hyogo prefecture on April, 2013. This institute possesses liquid hydrogen laboratory (Fig.1), which enables test and evaluation of liquid hydrogen utilization. Using this facility, demonstration test of superconducting magnetic energy storage (SMES) using liquid hydrogen for the study of "advanced superconducting power conversion systems for the effective use of natural energy" has been conducted since March 2014. This study was adopted by "Advanced Low Carbon Technology Research and Development Program (ALCA)".

Fig.1 Liquid Hydrogen Experiment Room
Prospect of Liquid Hydrogen Cooled Superconducting Power Apparatus and Carbon Dioxide Emission Reduction

Yasuyuki Shirai, Graduate School of Energy Science, Kyoto University, Japan

HTS (YBCO and BSCCO) superconducting wires are generally cooled by liquid nitrogen (77K). However, it is considered that excellent electro-magnetic properties of such materials are achieved with temperature of 20–40 K. Liquid hydrogen (LH$_2$: 20 K) is expected as a coolant for a HTS superconducting magnet because of its excellent cooling properties, such as large latent heat, low viscosity coefficient and so on.

On the other hand, for countermeasure to global warming problem, greenhouse gas, especially CO2 reduction is critical issue to solve. Hydrogen technology is one of the important solutions for innovative energy infrastructure. Both electricity and hydrogen are carbon free, clean and secondary energy, however, the electric energy is suitable for transmission and distribution, while the hydrogen energy is preferable for storage. Synergy effect of hybrid energy system with electricity and hydrogen is expected using hydrogen cooled superconducting power apparatus as key components.

Figure shows an image example of the future energy infrastructure with coordination of hydrogen energy and electrical energy by use of LH2 cooled superconducting power apparatus. Major hydrogen supply chain is produced by large liquid hydrogen tanker (similar to LNG tanker), which supplies liquid hydrogen to the hydrogen import base. The import base consists of hydrogen tank yard, hydrogen-gas turbine-driven hydrogen-cooled superconducting generator, hydrogen distribution station and so on. The liquid or gas hydrogen is transported to the substation/distribution base, which has a superconducting transformer, fault current limiters, SMES and cables cooled by LH$_2$. Hydrogen can be used as not only coolant of the superconducting power devices but also energy storage in electric power system.

It is necessary for a design of a HTC superconducting devices cooled by LH$_2$ to make heat transfer characteristic of LH$_2$, and electro-magnetic feature of LH$_2$ cooled superconductors clear. For these purposes, we have designed and fabricated an experimental setup, which can be used for investigating heat transfer characteristics of LH$_2$ in a pool and also in forced flow for wide range of sub-cooling and forced flow velocity, and for evaluation of electro-magnetic properties of superconductors cooled by LH$_2$. A Fundamental database of heat transfer in LH$_2$ has been preparing for pool-cooling and also for forced-flow-cooling. Critical current under external magnetic field of MgB2 wires cooled by LH$_2$ were investigated using the experimental facility.
Development of Advanced Superconducting Power Conditioning System to Utilize Renewable Energy Effectively

Takataro Hamajima, MAYEKAWA MFG. CO., LTD.

Recently, it has become an urgent and crucial issue to reduce global carbon-dioxide in order to develop sustainable society. The eco-friendly renewable energy should be used as a large amount of the electric power. However, a large amount of the renewable power may cause commercial power network unstable because of its intermittent property. It is important to compensate the fluctuating power produced by the renewable energy such as wind and solar power.

We proposed an advanced superconducting power conditioning system (ASPCS) composed of a hybrid energy storage system connected to renewable energy sources. The hybrid storage system is composed of hydrogen system (fuel cell (FC) – hydrogen tank - electrolyzer) and SMES system. The renewable power is resolved into fast and slowly changing components by stochastic prediction method based on Kalman filter algorithm. While the SMES compensates the fast changing component because it has quick response and large I/O power, the hydrogen system compensates slowly changing component because it has moderate response and large capacity. The SMES coil is wound with MgB$_2$ superconductor and cooled with liquid hydrogen (LH$_2$) which is supplied from liquid hydrogen station for FC vehicles from economical point of view. A thermo-siphon cooling system is adopted to keep the ASPCS facility safe against a flammable gas.

The ASPCS effectively fulfills a power balance by applying the prediction method to the fluctuating renewable power. The capacity of SMES is optimized by using the trend prediction for a number of wind power data. The overall electric efficiency of the ASPCS is analyzed for a typical wind generator.

In order to demonstrate the compensation of the fluctuating renewable power at a first step, we designed and fabricated a small scale ASPCS facility connected with a 1 kW class photovoltaic system. The hybrid storage system was composed of the SMES and the hydrogen system. The SMES coil was wound by Di-BSCCO and its storage energy was about 10 kJ. The SMES was cooled with LH$_2$ through thermos-siphon cooling system.

The test results showed that the SMES coil was successfully cooled down and the fluctuating components of the PV power were completely compensated.

Acknowledgment

This research was partly supported by “Advanced Low Carbon Technology Research and Development Program (ALCA)” of Japan Science and Technology Agency (JST)
Recent advances in REBCO coated conductors via the RCE-DR process

Sang-Im Yoo,

Department of Materials Science and Engineering, Research Institute of Advanced Materials (RIAM), Seoul National University,
Seoul 151-744, Republic of Korea
Phone: +82-2-880-5720, Fax: +82-2-887-6388, e-mail: siyoo@snu.ac.kr

High performance GdBa$_2$Cu$_3$O$_{7-d}$ (GdBCO) coated conductors (CCs), composed of GdBCO CCs/LaMnO$_3$/Epi-MgO/IBAD-MgO/Y$_2$O$_3$/Al$_2$O$_3$/Hastelloy, have been successfully fabricated via the RCE-DR (Reactive Co-Evaporation Deposition & Reaction) process by SuNAM Co. in Korea. Due to a very high conversion rate of the GdBCO film from an amorphous precursor film, an overall processing speed is faster than 120 m/h. A weak pinning property, however, has been the most serious problem for GdBCO CCs via RCE-DR, and hence there have been many efforts to improve the flux pinning properties of GdBCO CCs. Two approaches have been tried to solve this problem. One is to accurately determine the stability phase diagrams of REBCO phases for both stoichiometric and off-stoichiometric cation compositions. For this purpose, we have tried to experimentally determine the stability phase diagrams for YBCO, GdBCO, and SmBCO up to now, which will be presented. The other is to develop more effective pinning sites. Our efforts include the following. While refinement of Gd$_2$O$_3$ particles trapped in the superconducting GdBCO matrix was turned out to be very effective for $J_c$ improvement in all field directions, representing the isotropic pinning effect, the stacking faults piled-up along the c-axis of GdBCO, formed by the post annealing process, were found to be very effective for $J_c$ improvement for $H//c$ like columnar defects or nanorods. In addition, new approaches to refine the RE$_2$O$_3$ particles or perovskite oxides within the GdBCO matrix will be described.

This work was supported by the Power Generation and Electricity Delivery of the Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Korea government Ministry of Trade, Industry and Energy (No. 20131010501800).
Development of REBCO coated conductors utilizing artificial pinning center technology

Kaname Matsumoto
Dept. Materials Science and Engineering
Kyushu Institute of Technology
1-1, Sensui-cho, Tobata-ku, Kitakyushu 804-8550, Japan

R & D of high-performance coated conductors by using epitaxial REBCO superconducting films (RE=Y, Gd, Sm, etc.) has been rapidly progressing, where the introduction of artificial pinning centers (APCs), such as self-assembled nanorods and randomly distributed nanoparticles, is recognized as a most important technique for controlling the flux pinning properties of the coated conductors. Thinking about applications of coated conductors, desired features of $J_c$ are isotropic and high enough at 10-77 K under applied magnetic field. In this study, we report the promising results of flux pinning properties of REBCO films with high-density nanoparticle APCs at 10-77 K. Nanoparticle doped GdBCO thin films were prepared on single crystal and IBAD-MgO substrates by alternating pulsed laser deposition using REBCO target and BaHfO$_3$ (BHO) target as APCs. Volume fraction of APCs was tuned in the range of 3-10 vol. % by varying the supply of BHO. Superconducting properties were measured by PPMS. Maximum global pinning force, $F_{p\text{max}} (=J_c \times B, B \parallel c)$, of the 5 vol. % doped film reached 18 GN/m$^3$ at 77 K and 80 GN/m$^3$ at 65 K. We found, however, the low temperature properties of these films were excellent. $F_p$ values ($B \parallel c$) of the 5 vol. % film reached 350 GN/m$^3$ at 40 K and 750 GN/m$^3$ at 20 K, and exceeded 1000 GN/m$^3$ at 10 K. These data are comparable to the best results obtained by the films containing self-assembled nanorods such as BaZrO$_3$ or BHO, but plateau-like behavior of $F_p$-$B$ curves typically observed in the nanorods doped films were not identified for the present films. In addition, no maximum $F_p$ peaks at 10 K and 20 K were observed in $F_p$-$B$ curves below 9 T. We believe that periodically deposited BHO was randomly dispersed in the GdBCO films as nanoparticles instead of nanorods. We will show the recent results of our group including SmBCO films, and discuss the flux pinning mechanism of these films based on the results of microstructure observation and the time-dependent Ginzburg-Landau flux pinning simulation.
Development of Bi-based high-$T_c$ oxide and MgB$_2$ superconducting tapes and wires for CO$_2$ emissions reduction

H. Kumakura
National Institute for Materials Science
1-2-1, Sengen, Tsukuba, Ibaraki 305-0047 Japan

Bi-based high-$T_c$ oxide and MgB$_2$ tape and wire conductors can be used under liquid helium free conditions at around 20K, which are easily obtained by using a cryo-cooler or liquid hydrogen. Thus, these superconductors is expected to reduce CO$_2$ emissions in the industrial area of electric power system. In this presentation I will give an overview of three kinds of superconducting tapes and wires, Bi$_2$Sr$_2$CaCu$_2$O$_y$(Bi-2223), Bi$_2$Sr$_2$CaCu$_2$O$_y$(Bi-2212) and MgB$_2$ tapes and wires. Transition temperatures of these superconductors are 110K, 90K and 39K, respectively. Powder-in-tube(PIT) process is one of the most economical and simplest methods of tape and wire fabrications of these superconductors. In this method, a powder mixture of constituent materials is placed inside a metallic tube and cold-worked into tapes or wires; the wires and tapes are then heat treated to form superconductors.

For Bi-based oxides, c-axis grain orientation and high packing density of superconducting core are essential to obtain excellent superconducting critical current density, $J_c$. For Bi-2223, grain orientation is obtained by the combination of mechanical flat rolling and heat treatment. Usually two sets of rolling and heat treatment are applied. Densification of Bi-2223 superconducting core up to ~100% is realized by Sumitomo Electric Industries, Ltd.. They apply controlled gas overpressure(CT-OP) heat treatment under ~30MPa after the second rolling. This process enables the fabrication of km-long practical tapes with excellent and uniform $J_c$ values. The transverse cross section of CT-OP processed multi-filamentary Bi-2223 tape is shown in Fig. 1. For Bi-2212, slow solidification from the melting state is effective in obtaining grain orientation and also high density Bi-2212 core. Both Bi-2223 and Bi-2212 tapes show practical level $J_c$ values at temperatures above 20K, indicating that Bi-2223 and Bi-2212 can be used as conductors of liquid helium free superconducting device such as liquid nitrogen cooled power cables, superconducting magnetic energy storage (SMES) system, motors, transformers, high field magnet and so on.

$J_c$ value of MgB$_2$ tapes and wires is not sensitive to the grain orientation of MgB$_2$, but the density of MgB$_2$ core in the tapes and wires is the key factor which controls the $J_c$ of MgB$_2$ as in the case of Bi-based oxides. However, it is not easy to obtain high density MgB$_2$ core by the PIT method. The density of MgB$_2$ core in the PIT processed tapes and wires heat treated under 1 atmosphere with a usual furnace is only around 50% which decreases $J_c$ far below the practical level. Cold pressing before heat treatment or hot pressing of the PIT tapes and wires significantly increases the density of MgB$_2$ core and, hence, $J_c$ values. But these processes are not practical for the long tape and wire fabrications. A modified PIT method, internal Mg diffusion(IMD) method, significantly increases the density of MgB$_2$ core and realizes high performance MgB$_2$ tapes and wires. Transverse cross section of 19-filamentary IMD MgB$_2$ wires is shown in Fig. 1. IMD processed MgB$_2$ wires show almost practical level $J_c$ values in fields of 4-5T at 20K. Interesting applications of MgB$_2$ wires at around 20K are a liquid hydrogen cooled SMES system, cryo-cooler cooled MRI, motors and so on.

Fig. 1 Transverse cross section of PIT Bi-2223 tape and IMD MgB$_2$ wire.