Development of Bi-2212 Round Wire for High Field Applications

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The development of Bi-2212 round wires is receiving more and more efforts because of its potential use in ultra high-field (>25T) applications. In order to meet performance requirement for such applications, recent studies at OST have focused on 1) establishing Bi-2212 precursor powders to provide better results more consistently, 2) improving wire fabrication process for leakage-free longer length wire, 3) enhancing wire microstructure and Jc, Je by studying new configuration and sheath material, optimizing process conditions and 4) developing high performance larger insert coil through the winding-and-reacting method. The impact of precursor powders from different resources has been studied based on their composition, particle size, tap density, etc. New wire configurations, sheath materials and process conditions have been tested to enhance wire critical current density by means of increasing 2212/Ag interface area, filament homogeneity and density. The large leakage-free coils with good Ic have been made by enhancing sheath integrity and coil heat treatment homogeneity. The wire and coil performance improvement will be presented in detail.

Microstructural Features of High I_c, J_c Bi-2212 Round Wire Conductors

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The high-temperature superconductor (HTS) $Bi_2Sr_2CaCu_2O_y$ (Bi-2212) has recently reemerged as a viable candidate for low-temperature, high-field (> 20 T) magnet applications due to its high irreversibility field and unique characteristic, among the Cu-O based HTS, to be formed into a high-current, round multifilamentary wire. This work summarizes the microstructural features within fully-processed Bi-2212 round wire conductors. The best, short-length, round wires were found to have engineering critical current densities in excess of 1300 and 500 Amm^{-2} in self and 12 T applied fields at 4.2 K, respectively. Scanning and transmission electron microscopy (SEM, (S)TEM) were used to examine the key microstructural features and establish relationships between the structure and superconducting properties.

Electromechanical Behaviors of $Bi_2Sr_2CaCu_2O_{8+X}$ Multifilamentary Round Wire Fabricated with a New High Strength Dispersive-Strengthened Ag/Al_2O_3 Alloy

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Significant advances in the transport properties of $Bi_2Sr_2CaCu_2O_{8+X}$ (Bi2212) round wires have made it an appropriate option for high field magnet applications. In addition, I_c-strain dependency of Bi2212 conductor has been studied previously. Bi2212 is a brittle material, which shows an irreversible reduction in I_c with strain beyond a critical value. In this study, a new dispersive strengthened Ag/Al_2O_3 alloy has been fabricated to enhance the electromechanical properties of Bi2212 multifilamentary round wire. Here, microstructural characterization, tensile tests, and Vickers Micro-hardness tests are used to compare physical and mechanical properties of DS-Ag/Al_2O_3 and Ag/0.2wt%Mg alloys. Next, multifilamentary Bi2212 round wires are fabricated using both alloys and heat treated with partial melt process. I_c-stress/strain relationships are reported at self-field and in-field up to 8.5 T, and the results are compared.

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Overview of Current-Limiting Mechanisms in 2212 Round Wires – What they Are and How to Eliminate Them to Reach Useful Current Densities for High-Field Magnets

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2212 round wire has the preferred geometry to build very-high-field magnets. The round wire can be used in solenoids or formed into Rutherford cables. Je needed for dipole magnets for future accelerators is at least 600 A/mm^2 at 4.2 K, 20 T. However, current 2212 round wires can only achieve about 200 A/mm^2. The presentation will give an overview of the current limiting factors in 2212 round wires and methods we are pursuing to eliminate them.

This work is supported by DOE-HEP VHFSMC program, by NSF-DMR, and by the State of Florida.

Fabrication and characterization of green-state textured Bi-2212 ribbons and tapes

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The authors report on the development of a mechanically textured, low porosity Bi-2212 ribbon. The ribbons are fabricated by compacting fine-powder Bi-2212 in a counter-rotating roll set. Silver foil is used to seal the compacted ribbon to form a mono-core tape. Tapes are then subjected to mechanical deformations to reduce the cross sectional area and to increase density and texture of the conductor. Microstructure and texture of the as rolled ribbons will be reported and compared to green-state cores from multifilament wires processed using the oxide powder in tube (OPIT) process. Microstructure characterization of mechanically deformed tapes and reacted tapes are also reported.

Studies of porosity and correlation with J_c in Bi-2212 round and deformed wires

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Viability of BSCCO-2212 round wires for high field magnet applications is being investigated within the Very High Field Superconducting Magnet Collaboration (VHFSMC). BSCCO-2212 wires with different precursors were homogeneously flat-rolled to decreasing sizes to study the effect of deformation. After heat treatment in Oxygen, the transport properties of round and deformed samples at 4.2 K and up to 14 T were compared with studies of the microstructure of these samples to check for possible correlations between Jc and filament separation due to porosity. The wire made with granulate precursor was the most homogenous. The wires made with powder precursor showed instead non-monotonic behavior in I_c and even more so in the n-value. To check for intrinsic sources of J_c reduction, the Carbon content of the precursor was measured for the various wires and correlations with transport properties searched for.

Development of ex-situ MgB_2 wire with improved architectures for DC and AC applications

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Amongst the various benefits of the ex-situ method for the manufacturing of MgB_2 superconducting wires, the flexibility that it allows on the wire architecture is probably the most tangible and valuable one. While round wires with high filament count and high filling factor appears highly suitable for high current cable applications, and are currently developed in very long lengths, alternative solutions are now proposed for DC and AC windings. For DC magnets, a sandwich MgB_2 wire solution is currently proposed: a central MgB_2 tape conductor with high filling factor well above 20%, and without significant copper fraction, is soldered to two OFHC copper tapes after the final sintering, one on each opposite side. Thanks to this solution, the copper fraction and the wire critical current can be independently selected by adjusting the respective size of the superconducting and copper tapes. Thanks to the vicinity of the MgB_2 filaments to the neutral plane, a higher endurance to wire bending is also observed. Moreover, the RRR of copper is not depressed at all by the final sintering process that the superconducting wire has to undergo. Regarding AC applications, the ex-situ method has been made compatible with a full Titanium sheathed MgB_2 wire with fine filaments, that show clear filament electrical decoupling, and low AC losses thanks to the non-magnetic matrix, and comparable transport properties to the standard wires.

Hyper Tech Research will report on progress that has been made on developing magnesium diboride superconductor wires for research and commercialization efforts, with a specific emphasis on relating superconductor properties to the requirements of the application. The status of Hyper Tech Research's current demonstration projects for fabricating MgB_2 wire and coils for MRI, FCL, motors, and other applications will be presented.

Limits of Dopant Solubility in MgB_2 for B_{c2} Enchancement

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Much of the research on MgB_2 has been limited to heat treatment temperatures of 1000-1200 °C due to the volatility of Mg which leads to decomposition into MgB_4. This decomposition has constrained doping studies since many of the most interesting dopants have very high melting points (transition metal diborides), correspondingly high vapor pressure (Na), or low diffusion coefficients (C). In order to address these difficulties, we have constructed an induction heater which can reach temperatures greater than 2000 C using RF power injected into a high pressure vessel at 1500 psi (100 bar) in order to suppress Mg volatility. The sample is contained in a MgO crucible heated with a graphite susceptor. The solubility of Zr, Nb, Na and C will be determined using a combination of XRD and TEM to establish the actual solubility limit for these dopants. Superconducting property measurements will focus on measuring B_{c2} as a function of temperature.

Strain engineering for improvement in J_c and H_{irr} and H_{c2} in MgB_2

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An alternative mechanism for improvement of J_c has been reported by the author's group in SiC-MgB_2 composite which was made by pre-mixing SiC and B, followed by Mg diffusion and reaction. In contrast to the common practice of improving the J_c, and H_{c2} of MgB_2 through chemical substitution, it shows only a small decrease in the critical temperature, T_c, and little increase in resistivity, ρ. The further analysis indicated that, there is no SiC decomposition and C substitution, the enhancement of properties is induced by thermal strain caused by the different thermal expansion coefficients (α) of the MgB_2 and SiC phases for SiC-MgB_2 composite. The thermal strain in the MgB_2 phase was demonstrated with x-ray diffraction, Raman spectroscopy, and transmission electron microscopy. By taking advantage of residual thermal strains, we are able to design a composite with only a small decrease in T_c, and little increase in ρ, but a significant improvement in J_c and H_{c2}. The strain engineering was applied to the grapheme doping to MgB_2 where graphene has low to negative thermal expansion coefficient. It was found that the graphene doping at even 1% level achieved the optimally $J_c(H)$ performance (1×10^4 A/cm^2 at 5 K, 8 T), compared to the level for other carbon containing dopants at 5-10% level. The upper critical field has been enhanced to 13 T at 20 K for the optimal doping level. Another unique feature for grapheme doping is the very low resistivity, good grain connectivity in low field range and following δT pinning rather than δl for near all doped MgB_2. The Raman studies show that the active E_{2g} mode was split into two parts: the softened mode corresponding to tensile strain and the hardened mode attributed to the carbon substitution effect.

References:

R. Zeng *et al* Appl. Phys. Lett. 94, **42510** (2009)

X. Xu et al., Supercond. Sci. Technol. **23** , 085003 (2010)

Pinning in MgB_2 superconducting strands and thin films

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The nature of the pinning force density was investigated for both MgB2 superconducting strands and thin films. Undoped MgB_2 together with MgB_2 with 10 mol% SiC, MgO, and Al_2O_3 additions were made into monofilamentary superconducting strands. The critical current density, J_c, and pinning force density, F_p, of these strands were measured as functions of temperature and magnetic field. Pulsed laser deposition (PLD) techniques used to produce high-quality MgB_2 thin films were used to create multilayered films using SiC, MgO, and Al_2O_3 targets. Multilayered thin films were produced and measured in terms of superconducting magnetic properties such as critical current density, J_c, and pinning force density, F_p; these superconducting properties were compared to those of the strands. X-ray diffraction (XRD) was used to epitaxy of the multi-layered films as well as the strain via the Williamson-Hall technique. Transmission electron microscopy (TEM) was used to determine the orientation relationships between the MgB_2 and the normal-state multilayers, as well as the development of impurity phases. These results were used to clarify the properties of the strands with the same additions.

Significantly enhanced self-field J_c in diffusion processed MgB_2 superconductor

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Mg diffusion processing has been used as an alternative way to improve density of MgB_2 in the past five years. Controlling the starting magnesium (Mg) size, i.e., powder and lump, is the crucial for obtaining superior critical current density and upper critical field. By using a combination of synchrotron X-ray refinement and Raman spectra, we found that the lattice disorder was increased for the sample fabricated from Mg powder. This is a major cause of enhanced upper critical field, as confirmed by direct resistive transition analysis or by critical current analysis using the percolation model. In addition, the area fraction from Rowell's method for the sample fabricated from Mg powder is much larger than that of the Mg lump sample and almost comparable to the value for well-connected MgB_2 thin film. The critical current density at 1 T and 20 K for the sample fabricated from Mg powder reaches 2.5×10^6 Acm^{-2}. The mechanism for this enhancement is further explained by using TEM observations.

Microstructure and critical current density of Internal Mg Diffusion(IMD) processed mono and multi-filamentary wires

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We investigated the microstructure and critical current density J_c of mono-, seven-, and 19-filament MgB_2 composite wires prepared by an internal Mg diffusion (IMD) process. The reacted layer has dense microstructure with large amount of impurity phases such as MgB_4. The 10 mol% SiC monofilamentary wires had a J_c (calculated for the reacted layer) of ~10^5 Acm^{-2} at 4.2 K and 10 T in the early stage of heat treatment at 600~640°C, despite the critical current I_c being as low as ~10 A. At this stage, only the B area near the Mg core reacted with Mg to form a thin MgB_2 layer; a large amount of B remained unreacted. The Vickers hardness of the reacted MgB_2 layer in the IMD-processed wires is about 1300, which is much higher than that in powder-in-tube (PIT) processed wires. This suggests that the MgB_2 layer has a much higher density than the PIT-processed wire. Excellent J_c values with substantial I_c values can be obtained for multifilamentary wires when they were heated at ~640°C for 1 h. In this case, the B layer reacts almost completely with Mg to form MgB_2. The seven- and 19-filament wires had J_c values of 0.7-1×10^5 Acm^{-2} at 4.2 K and 10 T and 1.3×10^5 Acm^{-2} at 20 K and 3 T. These high J_c values are attributable to the high-density MgB_2 layer produced by the diffusion method. Void formation in the center of each filament is one of the problems associated with the IMD process that needs to be addressed in future studies.

Densification and its effects on critical current and microstructure of Bi-2212 round wires

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The Very High Field Superconducting Magnet Collaboration (VHFSMC) is working to make round wire $Bi_2Sr_2CaCu_2O_x$ (Bi-2212) conductor suitable for high-field magnet applications in the 20-30 T range. The critical current density of Bi-2212 wire is limited by connectivity. Using SEM of exposed filaments and synchrotron absorption microtomography of samples quenched from various steps in the process, we have shown that filament-diameter bubbles form during the melting of Bi-2212. These bubbles do not disappear in subsequent processing and they are a major current-limiting factor in Bi-2212 round wire. An analysis of multifilamentary high J_c wires shows that reducing porosity increases J_c(4.2 K, 5 T) from 900 A/mm^2 to 2880 A/mm^2. We are applying several different densification procedures aimed at further densifying the Bi-2212 filaments and we will report their effects on the critical current density and microstructure.

This work is supported by DOE VHFSMC program, by NSF/DMR, and by the State of Florida.

Development of high performance DI-BSCCO wire

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Since Bi2223 superconductor was discovered, Sumitomo Electric has been developing to manufacture superconducting wire using this material. The progress in several years is especially remarkable. DIBSCCO produced with CT-OP technique has exhibited 250A with the short trial wire as the highest critical current in 77K, self-field (corresponding to 600 A cm^{-1}) and 200 A with 1000 m-long wires. These high performances indicate that DI-BSCCO can be applied for superconducting apparatuses such as motors, magnets, transformers, power cables and so on. However, higher Ic is required so as to be applied for some efficient applications, such as more compact coils generating high magnetic field. We have been trying to improve critical current density by optimization of whole manufacturing process. In conference, the recent progress in Ic performance will be made a presentation.

Fabrication of Bi,Pb-2223 thin films using sputtering method

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$(Bi,Pb)_2Sr_2Ca_2Cu_3O_x$(Bi,Pb-2223) Bi-2223 is one of candidates for practical applications such as power cables, magnets, and motors. For these practical applications, the target of the critical current density of long length tapes is 400 A/mm^2. It is important necessary to show the high potential of Bi,Pb-2223. In this study, we fabricated Bi,Pb-2223 superconducting thin films using conventional sputtering method.

Bi-2223 thin films on $SrTiO_3$(100) were fabricated by sputtering of targets with various nominal compositions in the atmosphere of 0.33 torr pure oxygen atmosphere. After deposition, we carried out an post-annealing. The film was surrounded with Bi,Pb-2223 pellets during the annealing in order to avoid the vaporization of Bi and the installation of Pb. We carried out XRD measurements and resistivity measurements, and critical current density measurements.

The transition temperature of Bi,Pb-2223 after annealing achieved reached T_c^{zero} = 105 K, which value was almost same as bulk materials of Bi,Pb-2223. From the results of XRD measurements, we observed strong 00l peaks and sharp quadrapole, suggesting single phase of Bi,Pb-2223 and *c*-axis orientation. The J_c value of 2.1 x 10^5 A/cm^2 at 77K was obtained in Bi,Pb-2223 thin film annealed at 845^{o}C for 30 hours. The J_c value was much higher than commercialized Bi,Pb-2223 tapes, suggesting that Bi,Pb-2223 tapes still have the possibility of improvement and enhancement of J_c by controlling the microstructures.

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Optimization of thermal processing for Bi-2212 round wires using statistically designed experiments to improve reaction homogeneity and J_c

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To produce very high magnetic fields, on the order of 20 T and above, high-temperature superconductors are materials of interest for their high irreversibility fields and critical current densities (J_c). $Bi_2Sr_2CaCu_2O_x$ (Bi-2212) is of particular interest since a round-wire geometry has been developed and the production of long lengths is commercially viable. However, a somewhat complex heat treatment is required to fully react Bi-2212 wires, during which the powder filaments are partially melted for a specific time interval. This melt interval is of consequence for homogeneously reacting large thermal masses, such as magnet coils, since the time required for thermal equilibrium increases accordingly. Using multiple iterations of statistically designed experiments, we find that the critical current is especially sensitive to changes in the maximum process temperature and the duration of the melt. However, J_c may be increased by optimizing the other process variables, such as the ramp rate to that temperature. We show the critical current response surfaces for the processing parameters, and examine the corresponding microstructure. As this experimental method allows for sampling a large range of the process variables, we have found that the heat treatment may be optimized to maintain high J_c while extending the duration of time at the melt temperature to several hours.

Split melt processing of $Bi_2Sr_2CaCu_2O_x$/Ag/AgX coils

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Abstract: $Bi_2Sr_2CaCu_2O_x$/Ag/AgX (Bi2212) round wire is currently being considered for high field magnets due to its high J_c in very high field at 4.2 K and relative ease in winding and cabling into a wide variety of configurations. The processing requirements for Bi2212, however, are extremely stringent. Degradation due to interactions between the conductor and insulation, and leaking of oxide through outer sheath during heat treatment still limit the development of the transport performance of coils. To overcome these difficulties, a series of small test coils, wound with ~7 m long conductors, by Wind-React (W&R) and Split Melt Processing (SMP) are manufactured and characterized. Various aspect of thermo-processing, pre-anneal process, effects on microstructure and transport properties, compatibilities with conductor insulations are reported.

Index Terms—Bi2212, Superconducting magnet

Bi2212 round wire processing studies based on split melt processing and introducing saw-tooth processing

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A Recently developed method of magnet manufacturing, React Wind Sintering (RWS), led to a significant increase in J_c of multifilamentary Bi2212 round wires. In RWS, the conventional Bi2212 heat treatment is split into two sections, and the magnet is wound between these two sections. Detailed study of the strong correlations between transport properties of Bi2212 round wires and their microstructure indicated that many of the heat treatment parameters require further optimization. Here we introduce a new method of heat treatment, "saw-tooth processing" (STP) that includes performing several "splits" during heat treatment. Results from Differential Thermal Analysis (DTA) and microstructural studies using Scanning Electron Microscopy (SEM) show that with STP we are able to engineer the microstructure by increasing the portion of Bi2212 re-crystallized regions. The critical current is measured at 4.2 K in self-filed and in-field up to 5 T, showing increase relative to previous results.

Effect of Proton Radiation on the Critical Current and Critical Temperature of Bi-2212*

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HTS superconductors are being investigated for potential applications in particle accelerators in high field magnets operating at 4 K. When such magnets are also in a high-radiation environment, the effects of radiation on the superconductor need to be evaluated. In this paper we report on the performance of Bi-2212 superconductor irradiated with high-energy protons. 6 cm long samples of 0.8 mm diameter wire were irradiated at room temperatures in the Brookhaven Linac Isotope Producer, BLIP facility at BNL to five fluences, covering the range from 10^{16} to $4x10^{17}$protons cm^{-2}. The beam parameters for the irradiations were 42 μA and 142 MeV. After irradiation the critical current at 4.2 K was measured in fields of 0 to 8 T to quantify the effects of high-dose proton-induced radiation damage on the performance of the conductor. Wires typically had a pre-irradiation critical current of about 480-500 A at 0 T and 210-220 A at 5 T. The critical current is observed to be relatively unchanged for proton fluences up to 10^{17}protons cm^{-2}, and decreases linearly and rapidly past that threshold. The zero field critical temperature, measured resistively, decreases linearly with proton fluence and the transition width broadens appreciably. Details and significance of these measurements are discussed.

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Transverse and axial loading tests on ITER Nb3Sn TF strands and correlations with full-size ITER CICC performance

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Numerous manufacturers and different strand processing techniques are involved with the production of Nb3Sn strand material for ITER. The superconducting transport properties of the Nb3Sn layers strongly depend on the strain state. Hence, the thermal compression and the large transverse load in combination with the key choice for the cabling pattern of the ITER CICCs, will mainly determine their performance. Knowledge of the influence of axial strain, periodic bending and contact stress on the critical current (Ic) of the used Nb3Sn strands is inevitable to gain sufficient confidence in an economic design and a stable operation. We have measured the Ic and n-value of the actual ITER Nb3Sn strands from several manufacturers in the TARSIS facility, when subjected to spatial periodic bending and contact stress at a temperature of 4.2 K and in a magnet field of 12 T. The strands have also been subjected to uni-axial applied strain in compressive and tensile direction. The Ic, n-values and irreversibillity limit have been determined for strain varying from -0.8 % up to +0.6 %, at temperatures between 4.2 K and 10 K and magnet fields ranging from 6 T to 15 T. The strain sensitivity varies appreciably for different strand types but since the electromagnetic force is the driving parameter for strand bending in a CICC, the stiffness of the strands is essential. We present an overview of the results obtained so far and possible correlations with full-size short sample test in SULTAN.

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Submission Category:
1. ICMC-15 Mechanical Properties of LTS Materials
2. ICMC-17 Materials Properties of LTS Cables, Magnets and Machines
3. ICMC-07 Niobium3-Tin Superconductors

Paper Presentation: oral.

Metallographic examination of filament fracture in ITER Nb_3Sn TF strands after transverse and axial loading tests

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The high Lorentz forces applied to the magnet conductor wire during ITER operation may result in the fracture of the brittle Nb_3Sn filaments required for high field operation and irreversibly degrade the coil performance; consequently an extensive range of mechanical tests are being performed on the superconducting strand being produced for ITER. Nine to ten distinct multifilamentary strand geometries will be used in the ITER TF and CS coils, making it necessary to assess the impact of strand design on the susceptibility of the Nb_3Sn filaments to fracture. For this reason, a comprehensive metallographic analysis is being performed on a variety of strands that have undergone axial strain, periodic bending and contact stress tests at the TARSIS facility and through these tests have a known I_c degradation value (12 T, 4.2 K). To help understand the development of degradation, a series of strands were tested under uniaxial tension from zero strain to fracture in 0.1% strain increments. These specimens were examined in longitudinal cross-section and the periodic bending and contact stress samples were tested in a variety of orientations. Initial results show that filaments surrounded by voids were most susceptible to cracking and that away from voids, cracks were not observed until a threshold strain of ~0.6-0.8% was reached. A comparison of crack densities and locations and techniques for managing polishing damage will be presented.

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2. ICMC-17 Materials Properties of LTS Cables, Magnets and Machines
3. ICMC-07 Niobium3-Tin Superconductors

Paper Presentation: oral.

Characterization of Nb_3Sn Superconducting Strands under Wide Range Pure-Bending Strain

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Nb_3Sn superconducting wire is sensitive to strain, which degrades electromagnetic performance. The substantial operation degradations found during ITER model coil tests of high current Cable-in-Conduit Conductors have given rise to research aimed at understanding the mechanisms behind the degradations due to bending, transverse, and axial strains. The degradation of a single Nb_3Sn strand under pure bending is the focus of this paper. Pure bending tests have been conducted to quantify the degradation for the ITER Nb_3Sn strands. Based on the previously developed pure-bending sample holder for up to 0.8%, two improved types of sample holders were developed to cover pure-bending strains up to 1.4%. The test probe held two sample holders, with two strand samples in each sample holder. Bending errors and Lorentz force effects on the sample holders were evaluated. Critical current measurements as a function of bending strain between 0 to 1.4% were performed for ITER Luvata and Oxford internal tin wires at 15 T at the National High Magnetic Field Laboratory, FL.

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Extended fatigue testing of Nb_3Sn strand for fusion applications

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In tokamak fusion reactors, such as ITER, superconducting strands are subjected to repeated Lorentz force loading and unloading which may degrade performance over time. Therefore, fatigue testing of the Toroidal Field and Central solenoid conductor strands is the acceptance test for ITER. Brittle Nb_3Sn filaments inside ductile Cu sheaths allow the possibility of some elastic-plastic degradation that can lead to filament cracking and we are seeking to understand if there are design variables that might ameliorate such degradation. In this study we used advanced metallographic technique to observe the effect of 1000 to 30,000 loading cycles at axial strains from 0.4% to 1.14%. The strands examined include both bronze process and internal tin ITER production strands. After fatigue testing at 77 K the strands were polished in longitudinal cross section and imaged by Scanning Electron Microscopy (SEM). Crack densities within filaments as a function of strain and number of fatigue cycles were quantified from large montages covering ≈ 20 mm length of strand. The observed filament crack density is highly sensitive to the kirkendall voids produced in the Nb_3Sn reaction. Although in bronze process strands we saw many cracks in filaments surrounded by voids at lower strains, we rarely observed filament cracks away from voids until the axial strain exceeded 1.1%. A detailed comparison of the development of cracking under cycling loading for different strand types will be presented.

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Strain correlation between superconducting properties and electron-phonon coupling in Nb_3Sn

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Strain has a profound influence on the superconducting properties of Nb_3Sn, but the fundamentals of strain sensitivity are still poorly understood. A particular question is to what extent the electron density of states at Fermi level $N(E_F)$ is affected by strain. In an indirect approach to analyze the behavior of $N(E_F)$ as a function of strain, we calculate $N(E_F)$ from directly measurable parameters. The electron density of state is related to the normal state resistivity, the critical temperature and the critical magnetic field by the Ginzburg-Landau-Abrikosov-Gor'kov theory. These three parameters are experimentally determined through a resistance measurement of a binary stoichiometric Nb_3Sn sample as function of temperature, magnetic field and uniaxial tensile and compressive strain. The result of the calculation indicates that $N(E_F)$ increases with increasing compressive strain, which leads to the conclusion that the strain dependence of the superconducting properties of Nb_3Sn can partially be attributed to the strain dependence of the electron-phonon coupling.

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Novel methods for the critical current measurement of superconducting wires

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The critical current as a function of magnetic field of superconducting wires is commonly measured using about 60 mm short straight, or U-shaped samples, or about 1 m long samples on helical mandrels (so-called ITER barrels). Current redistributions, resulting from the limited length in perpendicular magnetic field, reduce the achievable voltage resolution in short straight, or U-shaped samples. We have introduced ‘wiggles’ in U-shaped short samples, which evoke the appropriate current distribution far before the region of interest, thereby mitigating undesired redistributions around the voltage measurement region, and enabling high voltage resolution measurements on short samples. The ITER barrel is designed for low to medium currents, but is commonly modified for high current wires. This often results in increased complexity, errors from reacted sample handling, preparation time, and cost. We have developed a method that retains the standard ITER barrel, but uses disposable, of-the-shelf plumbers copper tube fittings instead of machined end-rings, thereby resolving the aforementioned issues, and also solving a number of disadvantages of the original ITER barrel method. Both improved methods allow for an increased throughput and reliability of critical current measurements on superconducting wires.

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Evaluation of the critical current density of Nb_3Sn strands from magnetization measurements

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Motivated by the envisaged upgrade of the inner triplet magnets in the LHC (Large Hadron Collider), we have characterized the response of two types of Nb_3Sn superconducting wires to neutron irradiation by means of magnetization measurements. One of them is an RRP (Restack Rod Process) strand manufactured by Oxford Superconducting Technology, the other a PIT (Powder-in-Tube) strand produced by Bruker EAS. Several wire samples with a length of approximately 4 mm were cut from both strands. To simulate the expected radiation load in the vicinity of the interaction points inside the LHC, some of the samples were subjected to neutron radiation in the TRIGA Mark II reactor in Vienna. The magnetization measurements were performed in a SQUID magnetometer at temperatures ranging from 4.2 to 15 K and in magnetic fields of up to 7 T. The results of these measurements were used for the evaluation of the critical current densities of the wires based on the Bean model. The calculated J_C values strongly depend on the assumed geometry of the sub-elements in the wires (i.e. round or hexagonal, solid or hollow), which may explain certain discrepancies found between these values and the J_C values obtained from transport current measurements. Other possible sources of these deviations, including the field profile in the sub-elements and the effect of coupling, are currently being investigated.

Abstract to ICMC

Fast Neutron Irradiation Effect on Superconducting Properties of Nb_3Sn and Nb_3Al stands

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To investigate the effect of neutron irradiation on superconducting properties, fast neutron irradiation tests have been carried out with Nb_3Sn and Nb_3Al strands. The Nb_3Sn strand was supplied by Furukawa Electric Co. Ltd., and the Nb_3Al was fabricated at National Institute for Material Science. The critical current of the strands irradiated to about 3.0 x 10^{21} n/m^2 with 14 MeV neutron was measured using 28 T hybrid magnet and the magnetization property of irradiated sample of over 1.0 x 10^{24} n/m^2 at fission reactor was measured by SQUID at Oarai center of Tohoku University. In addition, the critical temperature was evaluated using the GM refrigeration system.

The critical current of the Nb_3Sn strand was increased clearly but the Nb_3Al was not increased. The critical magnetic fields of both strands under 100 mA were not shifted. The magnetization hysteresis (M-H curve) became wider after irradiation to 1.0 x 10^{22} n/m^2 but it shrank after over 1.0 x 10^{24} n/m^2 irradiation. The Nb_3Al strand irradiated to 4.3 x 10^{24} n/m^2, which showed non-superconducting, was heat treated at 800 C for 10 hours and it was clarified that the magnetization and the critical temperature recovered after heat treatment.

All these changes in superconducting properties would be explained by irradiation damage of the fast neutrons and the damage would be recovered by the proper heat treatment The presentation will include the performance results of a new test facility with 15.5 T superconducting magnet installed in a radiation control area at Oarai center.

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