Assessment of possible failure modes and non-destructive testing of the ITER pre-compression rings

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The pre-compression rings (PCRs) for the International Thermonuclear Experimental Reactor (ITER) represent one of the largest and most highly stressed composite structures ever designed for long term operation at 4K. Three rings, each 5m in diameter and approximately 300 x 300mm in cross-section, will be installed at the top and bottom of the eighteen “D” shaped toroidal field (TF) coils to apply a centripetal load of 70 MN per coil. The interaction of the 68 kA coil current with the required magnetic field to confine the plasma during operation will originate Lorentz forces that build in-plane and out-of-plane loads. The presence of the PCRs is essential to keep the stresses below the acceptable level for the ITER magnets structural materials.

Each PCR will be pre-loaded at RT and cooled to 4K. They are designed to withstand various thermal cycles reaching >400 MPa hoop tension and >50 MPa compression without degradation. The rings will be fabricated (pre-dominantly) by hoop wound S-glass tow to result in a high glass content (>65 volume %) structure. During manufacture emphasis will be placed on obtaining a structure with a low void content (<1.5%) and that is free from inclusions, faults, cracks and de-laminations. The biaxial loading conditions that exist in the PCRs can lead to complex behaviour patterns while the few existing studies on ring like structures have been limited to testing tubular specimens with axial loading and either internal pressure or a torsion load applied. This paper will study the possible failure modes of the PCRs and consider available non-destructive evaluation techniques that may be applied to the full scale rings after manufacture.

Radiation Effect on Interlaminar Shear Strength of the Electric Insulation System with Cyanete Ester and Epoxy Blended Resin

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In this study, some blended resins with different mixture ratios, cyanate ester:epoxy in weight; 100:0, 40:60, 30:70 and 20:80, were prepared and laminate structure stacked with 10 layers of polyimide film and 11 layers of glass cloth in 2.5 mm thick was filled with the blended resin by vacuum impregnation. Glass transition temperatures (Tg) of the hardened resins and the heat generation during the hardening process were measured by a differential scanning calorimetry (DSC). The composite samples with 10 x 15 x 2.5 mm were machined out and irradiated in fission reactor, JRR-3, and interlaminar shear strength (ILSS) was evaluated at 77 K by short beam method.

The DSC measurement showed (1) Tg increased as an increase of cyanate ester fraction under the maximum curing temperature of 150 C, and (2) there were two exoergic reactions in the hardening process. C-13 nuclear magnetic resonance analysis clarified that the triagine ring would be formed after the first exoergic reaction at 100 C and the amount of triagine ring would be reduced after the second reaction on the temperature rising process to 150 C because of formation of oxazolidinon with opened epoxy.

Although 100% cyanate resin composite irradiated up to $1x10^{22}$ n/m^2 did not show significant ILSS drop, the blended resin composites dropped the ILSS drastically. In the JRR-3, about 2.5 MGy/h of gamma ray is supposed and about 500 MGy in total would be irradiated during the 10^{22} n/m^2 neutron irradiation. Therefore, it is considered that the radiation with heavy gamma ray dose will degrade the ILSS of the composite with opened epoxy molecular structure and less amount of triagine ring.

Qualification of a cyanate ester epoxy blend supplied by Japanese industry for the ITER TF coil insulation

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During the last year, two cyanate ester epoxy blends supplied by European and US industry have been successfully qualified for the ITER TF coil insulation. The qualification of a third CE blend supplied by Industrial Summit Technology (IST, Japan) is currently under way. The results of this program will be presented in this paper.
Sets of test samples were fabricated under the same conditions. The reinforcement of the composite consists of wrapped R-glass / polyimide tapes, which are vacuum pressure impregnated with the resin. The mechanical properties of this material were characterized prior to and after reactor irradiation to a fast neutron fluence of $2x10^{22}$ m^{-2} (E>0.1 MeV), i.e. twice the ITER design fluence. Static and dynamic tensile as well as static short beam shear tests were carried out at 77 K. In addition, stress strain relations were recorded to determine the Young's modulus at room temperature and at 77 K. The results will be compared in detail with those of the previously qualified materials from other suppliers.

Cryogenic tensile strength characterization of advanced woven fabric composites

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Composite materials (e.g., carbon fiber reinforced polymer (CFRP) and glass fiber reinforced polymer (GFRP) composites) have received increased attention for applications in cryogenic environment. Hence, the cryogenic mechanical properties of composite laminates must be characterized and fully understood. However, the determination of composite mechanical properties, especially the ultimate tensile strength, at cryogenic temperatures is not straight-forward. This is a result of the high strength, stiffness, and anisotropy of polymer matrix composite materials. Also, the cryogenic testing problems include that the specimen slips out of the test grips during testing.

In this study, a combined numerical-experimental method is presented for the evaluation of the tensile strength properties of woven CFRP and GFRP composite laminates at cryogenic temperatures using the open hole specimens. The cryogenic open hole tensile tests were carried out, and the failure loads were obtained. From the microscopic examinations of the fracture surfaces, the length of the damage zone at the hole edge was measured. The experimentally determined failure load and damage zone length were applied to the finite element model to estimate the cryogenic tensile strength of the unnotched woven laminates. The validity of this approach is discussed by comparing the predictions with existing experimental data.

Mechanical response of nonwoven polyester fabric/epoxy composites at cryogenic temperatures

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A significant advance in the performance levels of high temperature superconducting (HTS) materials has made them suitable for commercially viable applications such as coils and cables. In recent years, epoxy-based composites reinforced with nonwoven polyester fabric have been developed for superconducting applications because of their excellent electrical properties. In order to have confidence in the safety and reliability of the composite components, designers must possess a good understanding of the physical and mechanical characteristics of nonwoven polyester/epoxy composites under appropriate service conditions. In this work, we characterize the cryogenic responses of nonwoven polyester/epoxy composites under tension, compression and bending. Tension, compression and flexural tests were performed at room temperature and liquid nitrogen temperature (77 K) to evaluate the elastic and strength properties of the composites. The test specimens were produced from the composite cylindrical components. Microscopic observations were also made on the test specimens. The temperature dependence and anisotropy of the composite properties were examined based on the obtained results.

Internal tin Nb_3Sn development for large scale applications

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The development of high performance internal tin strand has led to greater use of Nb_3Sn in large scale magnets such as those for particle accelerator and fusion applications. We continue to develop strand to meet application-specific requirements that go beyond the basic need of high critical current density. We will present our latest data on single barrier strand being produced for ITER TF use, and update the status of our multiyear production campaign for ITER. Such strand has typical non-Cu J_c values over 1100 A/mm^2 (12 T, 4.2 K) with hysteresis losses less than 700 mJ/cm^3 over the non-Cu volume. For high field magnet applications, higher J_c values are achieved using a distributed barrier design. We will present our latest data on high J_c strands doped with Ta or Ti, and update the progress made in reducing the effective filament diameter by increasing the number of subelement rods incorporated into the final restack billet.

Compositional and structural effects on the properties of superconducting Nb_3Sn

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Although Nb_3Sn is one of the most widely used superconductors, fundamental understanding of how varying composition in this non-stoichiometric A15 compound affects the superconducting properties and the low temperature structural transformation is still unclear. This uncertainty compromises further development of Nb_3Sn conductors which are inherently compositionally and perhaps structurally inhomogeneous. In this work, we report recent results on highly homogeneous bulk A15, in which the Sn content has been varied. We have examined whether the low temperature tetragonal transformation occurs, fully characterizing the samples too by X-ray diffraction, SEM, EDS, normal state resistivity, specific heat, and VSM and transport measurements of H_{c2}. Surprisingly, we find that homogeneous bulk A15 samples (Sn varying from 23.3 to 24.6 at% Sn) display identical upper critical field H_{c2}(0.3 K) ~ 29± 0.2 T that is independent of whether the sample undergoes the cubic to tetragonal transition. This result is in marked contrast to the most widely used multiple-source data compilation that shows a strong depression of H_{c2}(0K) from 29 T to 21.4 T on exceeding an A15 composition of 24.5% Sn when the structure become tetragonal. Our results do show that H_{c2}(T) is better correlated to the resistivity than to the at%Sn or the occurrence of the cubic-tetragonal transition that only occurs for near-stoichiometric Nb_3Sn.

Nb_3Sn conductor dimension changes during heat treatment

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During the heat treatment of Nb_3Sn coils for accelerator magnets the conductor material properties change significantly. These effects together with the changes of the conductor dimensions during heat treatment may introduce large strain in the coil.
The goal of this study is to understand the thermal expansion and contraction of Nb_3Sn strands, cables and coils during heat treatment. Several measurements on strands and cables were performed in order to have sufficient inputs for finite element simulation of Nb_3Sn dimensional changes during heat treatment. In this paper the results of measurements of RRP Nb_3Sn conductor used in US LHC Accelerator Research Program (LARP) magnet program are discussed. Some conclusions are drawn on the Nb_3Sn coil elements behavior during the heat treatment.

Conductor Development for Accelerator Magnets Based on Tin-in-Tube Nb_3Sn Wire

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A major thrust in Fermilab's accelerator magnet R&D program is the development of Nb_3Sn wires which meet target requirements for practical magnets, such as designs with 217 or more restacks and sub-element size of less than 20-30 μm that, in addition, do not break or merge during the cabling process. The performance of a number of strands with 217 restack designs produced by Hyper Tech with different amount of Cu around the sub-elements was studied in the round and deformed wires, and in Rutherford-type cables with various packing factors. To optimize the maximum plastic strain, finite element modeling was also used as an aid in the design. Results of mechanical, transport and metallographic analyses are presented for both wires and cable samples.

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Progress on Application and Manufacture of Tube Type Nb_3Sn Superconductor

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In this paper, tube-type processed Nb3Sn strand has been continuously investigated. The number of subelements was increased to 1387 (1248 subelements plus 139 Cu filaments) by increasing the size at which restacking is carried out. The billet was drawn down and tested at a wire diameter of 0.7 mm, where the subelements are 12 µm in diameter. Jc value and AC losses will be presented in the paper. As a successful application of tube type strand on undulator coil, the 192-subelement strand was drawn down to 0.5 mm which has subelement size of about 25 µm, and wound in undulator former. The wound undulator was annealed and tested. The result will be reported in this paper.

Studies for Rod-in-tube and Tube-type Nb_3Sn strands optimized for different operational regimes

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High performance Rod-In-Tube (RIT) and Tube-type Nb_3Sn strands were optimized for field (15T) and low field (2T) operation. The RIT strands had 61 and 91 subelements and the Tube-type strands had 271 and 919 subelements. RIT and Tube-type strands had the same 0.7 mm OD. High field optimization (B_{c2} improvement) and low field optimization (stability improvement) were attempted by utilizing higher reaction temperatures in the range of 650-800C. Short samples were reacted under flowing argon. M-H loop measurements were used to extract magnetic J_c as a function of B and T. Resistive transitions were used to obtain B_{c2} and B_{irr}. SEM-EDS was used to measure fine-grain A-15 layer thickness, grain size, and stoichiometry.

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