Seminar

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Institute for Plasma Research

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Title: Design, development and testing of dissimilar material joints for cryogenic services of superconducting fusion machine

Speaker: Mr. Rajiv Sharma
Institute for Plasma Research, Gandhinagar

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Abstract

Cryogenic components such as electrical insulation breaks (IB) and cryogenic vacuum barriers (VB) are used as dissimilar material (DM) joints in fusion devices. These specific components are installed in hydraulics of superconducting (SC) magnets coils and current feeder system of SC fusion machines. Its function is to isolate the vacuum between the SC current feeder system (CFS) and the cryostat of tokamak and provides electrical isolation up to 5 kV DC voltage when SC magnets quenches. The DM joints were developed in order to fulfill the requirement of SST-1 device. Due to complexity of SC fusion device, it is essential to develop leak tight and Paschen tight such components. For fabrication of DM joints, there is need of cryo compatible insulation material and epoxy resin systems for bonding as the key components. To achieve the objective and completeness of the defined problem, the research effort was divided into three parts, namely, development of insulation material and epoxy resin system, DM joint design, fabrication and testing, and neutron-resistant insulation material development, which are described in the subsequent paragraphs.

The insulation material must withstand the temperature from 300 K to 4.5 K and helium leak tightness of 1.0 x10^{-8} mbar-l/s under its service condition. In DM joints of GFRP composite and metal, thermal shrinkage is one of the main parameter needs more attention for the design aspect. S-glass insulation material is selected due to high fiber tensile strength and modulus, low thermal conductivity, low out gassing rate, low permeability, low thermal contraction and high strength at cryogenic temperature than E-glass, R-glass and ECR glass. Boron free S-glass, 360 Tex was used in roving form bonded with developed epoxy resin that formed thermoset cured GFRP composite structures in form of DM joints. To validate the insulation material, the mechanical and electrical performance tests of insulation sample according to ASTM standard, insulation tube and final complete DM joints were carried out at 300 K and 77 K. The epoxy resin needs to have low viscosity, good adhesion, and resistance to moisture, long usable life, and high toughness at cryogenic temperatures. Two component modified diglycidyl ether of bisphenol-A (DGEBA) resin was formulated and optimized with the silane coupling agent, toughening agent, and hardened with different types of curing agent hardeners, such as amine and anhydride with different ratios. The polyamine hardener based epoxy systems accepted and offered better adhesive properties at cryogenic temperature compared with the anhydride-based hardeners. Various imported and local epoxy resins were procured and tested for the selection and fabrication of DM joints. In order to validate epoxy resin system, physical, thermal, mechanical, and electrical performance tests were performed on the epoxy samples and final components at 300 and 77 K.

The epoxy resin bonded DM joints consists of S-glass GFRP composite and SS316L, were designed and fabricated using the wet filament winding process. The two SS conductor tubes are separated and bonded with an inner insulation tube, making a primary helium leak-tight joint, and outer insulation by overwrapping on a passed bonded assembly.Due to anisotropic behaviour, there are axial and radial thermal stress acting on the system. The shrinkage of SS tubes depend upon the thickness of SS conductors tube and inner composite tube and overall length of component and tensile force exist in bond between outer insulation and SS tubes. The thermal contraction and distance between the conductors were optimized for the Paschen discharge event and electrical voltage requirement. The contour geometry and sharp edge surfaces have taken into account the electric field strength and dielectric breakdown phenomenon criteria. The filament winding process parameters such as fiber angle, glass fiber and resin content fiber speed and torque were optimized to fabricate the inner insulation tube and outer insulation winding. The DM joints underwent rigorous performance testing at 0-30 bar (g) pressure, helium leak tightness of $\leq$ 1.0x10^{-8} mbar-l/s, thermal cycle at 77 K and 10 kV electrical tests during each stage of fabrication. Investigations were conducted to examine the helium leak tightness under mechanical loading conditions, including tensile, compressive, bending, torsion, and pull-load failure tests at 300 K and 77 K. To overcome the flexibility issue, radial thermal stress, and electromagnetic forces generation during current charging under cryogenic load conditions, cryogenic bellows were developed, tested, and installed with VB. For repeatability, acceptance, and reliability, hundreds of DM joints of glass fiber and metal were fabricated, with a failure rate of 4-5% observed. The developed GFRP epoxy-based VB overcomes the important issues of brittle failure and electrical breakdown occurrence. DM joints were installed and validated at operating conditions in the SC bus bar of the current feeder system of SST-1 machine.

The insulation material development was very challenging especially when it is used in neutron radiation environment. The radiation spectrum and the thermal stresses at the magnet location significantly influence the mechanical behavior of the insulation material and therefore this imposes high demands on the insulation material and cryogenic components performance. The neutron irradiation experimental was carried out on GFRP insulation sample for $1.0x10^{21}$ n/m^2 neutron fluence and 0.4 MGy gamma radiation dose at Fast breeder test reactor (FBTR). No significant degradation (about 2 – 3%) was observed in mechanical and electrical performance of insulation material.

These developed component is purely customized in nature and not readily available in the local or international market. This insulation material and components can be used for future indigenous SC magnet fusion machines and electrical isolation experiments purpose at low temperature. In-house developed components save significantly higher costs than imported ones. The development has showcased the indigenous and ‘Make in India’ concept by providing a cost-effective and innovative solution, which increased availability according to requirements, eliminates the dependency on foreign agencies, and reduced long delivery of the item. This doctoral research project will cover and present the design, development, fabrication process, mechanical and electrical analysis and performance tests of DM joints at 300 K, 77 K, and 4.2 K, as well as the development and performance tests of epoxy resin system and glass fibre insulation material, and the performance of GFRP insulation material in neutron environment.

Keyword: Dissimilar material joints, Stainless steel to glass fiber, GFRP insulation, Epoxy resin, Vacuum barrier, Electrical insulation breaks, Superconducting fusion tokamak