TEST RESULTS OF A Nb_3Sn QUADRUPOLE COIL IMPREGNATED WITH RADIATION-RESISTANT MATRIMID 5292*

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Abstract

The fabrication process used for Nb_3Sn accelerator magnets comprises coil reaction at high temperature and then impregnation with epoxy to restore the insulation electrical and mechanical properties. The traditional epoxy has a low radiation strength which limits the lifetime of accelerator magnets operating in severe radiation environments. Fermilab performs studies of Matrimid® 5292 - a bismaleimide based material, as a radiation-resistant alternative to epoxy. This material has appropriate viscosity and pot life, and provides excellent mechanical, electrical and thermal coil properties. Two Nb_3Sn coils, a 1 m long quadrupole coil and a 2 m long dipole coil, were fabricated and impregnated with Matrimid. The quadrupole coil was tested in a quadrupole magnetic mirror at 4.5 and 1.9 K. Coil test results are presented and compared to the results for similar coils impregnated with epoxy.

INTRODUCTION

Fermilab is developing Nb_3Sn magnets for high-energy accelerators, including quadrupoles and dipoles for the Large Hadron Collider (LHC) upgrades [1, 2], Muon Collider [3], etc. As the energy of accelerators increases the radiation load on magnets goes up too, becoming a key factor limiting magnet lifetime.

Insulation, as a main component of any electrical device, including accelerator magnets, should have good electrical, mechanical and thermal properties, and be compatible with magnet fabrication and operating conditions. The manufacturing process used for Nb_3Sn accelerator magnets includes a coil reaction at temperatures of ~650C followed by coil potting with epoxy to restore the insulation mechanical strength and provide the required electrical and thermal properties. However, epoxy is the first component that incurs radiation damage.

Studies to replace epoxy as an impregnation material for Nb_3Sn coils with high radiation-resistant material like polyimide solutions started at Fermilab ten years ago [4]. The studies concentrated on Matrimid®5292, a bismaleimide based material, which has an appropriate combination of viscosity and potlife, and provides excellent coil mechanical, electrical and thermal properties.

Two Nb_3Sn coils, a 1 m long quadrupole coil and a 2 m long dipole coil, were recently fabricated at Fermilab and impregnated with Matrimid. The quadrupole coil was tested in a quadrupole mirror structure. This paper summarizes the experience of impregnating Nb_3Sn coils with Matrimid 5292, and reports the test results for the quadrupole coil.

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COIL FABRICATION

Matrimid® 5292 is a hot-melt bismaleimide solution which belongs to the category of radiation resistant materials. Compared to CTD-101K epoxy [4], traditionally used for Nb_3Sn accelerator magnets, it has similar mechanical properties but slightly higher thermal conductivity and dielectric strength [4, 5]. However, a number of issues need to be resolved to demonstrate that it can be used for potting accelerator magnet coils. Primarily, Matrimid requires significantly higher potting and cure temperatures than CTD-101K. Furthermore, Matrimid shows tradeoffs between low viscosity and long pot life. The rapid rise in Matrimid viscosity at reduced temperatures also poses certain challenges for the impregnation equipment. To avoid Matrimid freezing and premature curing, higher potting temperatures have to be used, and temperatures of all exterior lines must be controlled. However, the higher temperatures significantly reduce pot-life.

Two Nb_3Sn coils, a 1 m long quadrupole coil and a 2 m long dipole coil, have been fabricated and impregnated with Matrimid. The dipole and quadrupole coil cross-sections are shown in Fig.1. Both coils have two layers wound from a single piece of a Rutherford cable made of Nb_3Sn strand 0.7 mm in diameter. The cable used in the quadrupole coil consists of 27 strands and has a width of 10.03 mm and a thickness of 1.26 mm. The cable used in the dipole coil consists of 40 strands and has a width of 14.69 mm and a thickness of 1.25 mm. The cross sectional area of the dipole coil is about 5 times larger than that of the quadrupole coil. The coil designs and impregnation procedures with CTD101K are described in [6, 7].

Details of the coil impregnation with Matrimid are reported in [8]. The impregnation temperature for Matrimid was 125 C and the potting time for the 1 m long quadrupole coil was 15 min. The potting time of the 2 m long dipole coil increased to ~45 min. After impregnation the coils were rested at 125 C and atmospheric pressure during 1 hour before ramping to cure temperature of 200 C.

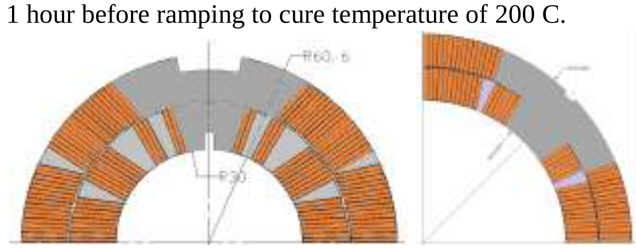

Figure 1: Cross-sections of the 60 mm dipole (left) and the 90 mm quadrupole (right) Nb_3Sn coils.

Fig. 2 shows pictures of both coils after impregnation. The coils had a smooth and consistent external finish. The cross-section of both coils was measured in the free state using a 3D coordinate measuring machine (CMM). The measured coil sizes are similar to the coils impregnated in the same tooling with CTD101K. The dipole coil was then sectioned in several cross-sections and the quality of impregnation was examined and confirmed to be excellent.

Figure 2: The 1 m long quadrupole coil (left) and the 2 m long dipole coil (right) impregnated with Matrimid.

TEST STRUCTURE ASSEMBLY

The quadrupole coil was assembled into a magnetic mirror structure, a device used to test an individual coil at cryogenic temperatures and operating conditions (the level and distribution of magnetic field and Lorentz force) close to that of a real magnet. The details of the quadrupole mirror design, parameters and assembly procedure are reported in [9, 10].

Fig. 3 shows the cross section of the mirror structure with the quadrupole coil, an iron mirror replacing the three missing coils, an iron yoke and a bolted stainless steel shell. The thicknesses of coil radial and mid-plane shims are adjusted to achieve the desired preload at room temperature. The side shims, placed onto the horizontal surface of the mirror block side "ears", are used to adjust the preload during pressing and control the preload during cool-down.

The final azimuthal coil pre-stress of the quadrupole mirror (labeled TQM05) at room temperature was 125-140 MPa. An axial load to each coil end of 5 kN was applied and controlled by two instrumented bolts (bullets) on each end through 50 mm thick stainless steel end plates. The maximum coil pre-stress after cooling down is estimated as 150-165 MPa, the same as other quadrupole mirrors assembled with similar coils.

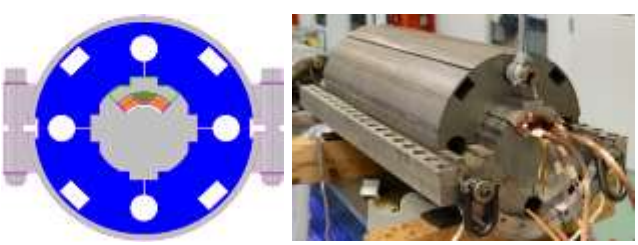

Figure 3: Quadrupole mirror schematic cross-section (left) and TQM05 cold mass inside the bolted half-skin (right).

COIL TEST RESULTS

The quadrupole mirror TQM05 was tested at the FNAL Vertical Magnet Test Facility. The magnet was tested in two thermal cycles. The magnet test plan included quench training and studies of ramp rate dependence both at 4.5 and 1.9 K, as well as measurements of temperature dependence of magnet quench current and coil Residual Resistivity Ratio (RRR). The average coil RRR in TQM05 was ~250.

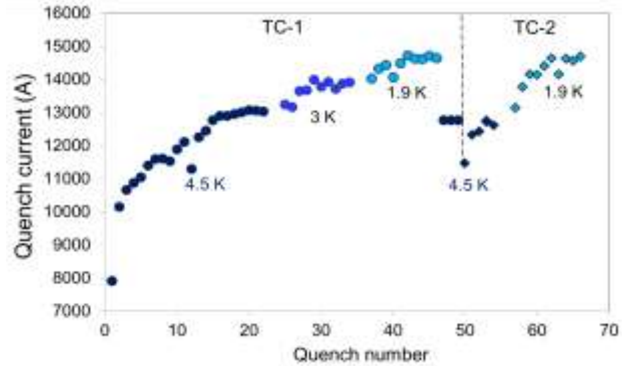

Figure 4: Magnet training in two thermal cycles (TC).

Magnet training quenches at different temperatures in both thermal cycles (TC-1 and TC-2) are shown in Fig. 4. Magnet training started at 4.5 K. After some training the quench current reached plateau at 13.0 kA which corresponds to B_{max} in the coil of 11.8 T. Then training was continued at 3 and 1.9 K. After training TQM05 reached a maximum quench current of 14.73 kA or a field in the coil of 13.3 T. At all temperatures, all training quenches started in the coil pole turns where the magnetic field in the coil reaches its maximum. At all the 3 different temperatures the maximum quench current reached 97-98% of the corresponding SSL. After training at 1.9 K the maximum quench curent at 4.5 K reduced from 98% to 96% of SSL.

After a thermal cycle the magnet revealed some small de-training but after few quenches reached the previous quench current plateau at both temperatures.

The ramp rate dependences of magnet quench current at 4.5 K and 1.9 K are shown in Fig. 5. All ramp rate quenches started in the pole turns. It indicates that the interstrand currents in the cable are small.

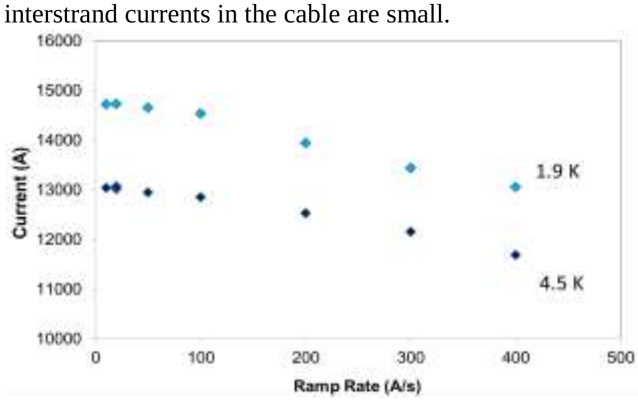

Figure 5: Ramp rate dependence of magnet quench current.

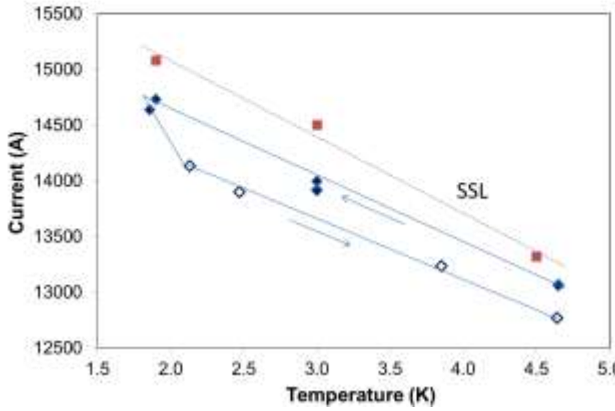

Figure 6: Measured and calculated (SSL) magnet quench current vs. bath temperatures.

The temperature dependences of the quench current measured after training at 4.5, 3 and 1.9 K as well as during the temperature increase from 1.9 to 4.5 K, and calculated (SSL) are shown in Fig. 6. TQM05 shows expected monotonic increase of quench current with temperature decrease. All quenches initiated in the coil pole turns. As it seen in Fig. 6, some small quench current degradation occurred after magnet training at 1.9 K.

A comparison of the training data for the coil impregnated with Matrimid (TQM05) with coil #19 (TQM01), a regular TQ coil made of the same RRP-54/61 strand, and for coils #34 (TQM03) and #35 (TQM04), TQ coils made of RRP-108/127 strand, all impregnated with CTD 101K epoxy and tested in the same structure [9, 10] is shown in Fig. 7. Similar performance for all the coils including some small degradation at 4.5 K after magnet quenching at higher currents at 1.9 K is clearly seen.

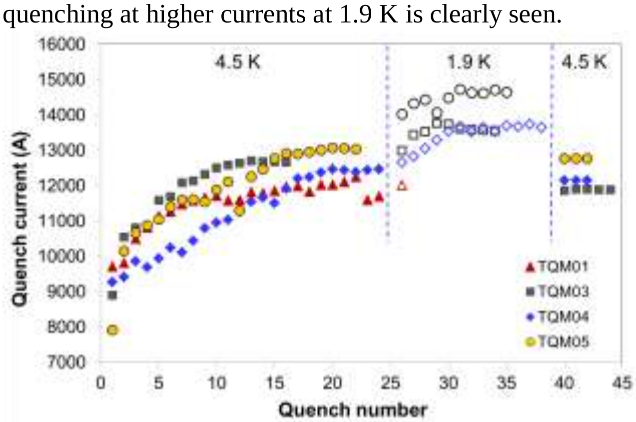

Figure 7: Comparison of the coil quench performance.

CONCLUSION

Two Nb_3Sn coils, a 1 m long quadrupole coil and a 2 m long dipole coil, were successfully impregnated with Matrimid, a bismaleimide based material, which has a radiation resistance significantly higher than traditional epoxy used currently for Nb_3Sn R&D coils. The 1-m long quadrupole coil has been tested in a quadrupole mirror structure. Quench training, ramp rate and temperature dependences are consistent with the data for other coils of similar design impregnated with standard epoxy and tested in the same mirror structure. Some small retraining of the Matrimid-impregnated coil was observed and needs to be further studied and understood. A scale up of the coil impregnation technology using the Matrimid for coils up to 4-6 m long is the next step in the program.

The results of this work demonstrate that Matrimid could be considered as a potting material for the Nb_3Sn accelerator magnets operating in severe radiation environments. This is important for Nb_3Sn accelerator magnet technology and will have a significant impact on IR quadrupoles for the LHC luminosity upgrade being developed by LARP. Also, it will impact the development of magnets for a muon collider, where all SC magnets including IR, storage ring and other magnets in the chain are irradiated by muon decay products.

ACKNOWLEDGMENT

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