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Fabrication and Testing of a High Field Dipole Mechanical Model

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Abstract—As a first step towards the development of a high field Nb_3Sn superconducting dipole for a Very Large Hadron Collider (VLHC), a short mechanical model was built and tested at Fermilab. The aim of this work was to develop simpler fabrication techniques and test new structural materials to use in the dipole model. The coil design was based on a two-layer, $\cos(\theta)$ approach. The end parts were designed using ROXIE magnet optimization program and manufactured using a 6-axis EDM machine. The two layers of each half-coil were wound using one piece of cable without any interlayer splices. After winding, a ceramic matrix was applied to the each half-coil and the coil was cured under compression at 150 °C. The two half-coils were then assembled together in a reaction fixture for heat treatment at 450 °C for 8 hours. After reaction, the coils were placed in a curing fixture for epoxy impregnation. Finally some mechanical and electrical tests were performed after which the coils were sectioned to check the cable positioning and impregnation quality. This paper summarizes the results and experience obtained from the mechanical model.

I. INTRODUCTION

Fermilab, in collaboration with LBNL and KEK, is working on the design of a high field Nb_3Sn dipole magnet for possible use in a future Very Large Hadron Collider (VLHC). The conceptual design of the first dipole model is based on a wind-and-react technology and a 2-layer cosine-theta coil structure [1]. This technology requires a cable insulation capable of withstanding the Nb_3Sn reaction temperature of about 700 C for 100-600 hours. Traditionally S2 fiberglass or mica-glass insulation has been used to fabricate coils, as was done for the several Nb_3Sn dipole magnets built around the world. This insulation becomes very weak after reaction and requires careful handling. On the other hand, new ceramic based insulating materials have recently become available [2]. To make a choice of the coil fabrication process and to acquire experience in dealing with specific materials, a mechanical model of a high field dipole has been designed and fabricated. The goals for the mechanical model were:

- to select a CAD-CAM software for the end parts design and to find an economical technology for the end parts fabrication,
- to set up the equipment and tooling necessary for the coil fabrication,
- to find a proper technology for cable insulation and coil winding,
- to verify the chosen coil fabrication technique, and
- to verify the coil impregnation procedure.

This paper describes the various steps involved in the magnet fabrication and summarizes the experience gained from the mechanical model.

II. COIL FABRICATION

A. Cross-Section and End Parts Design

The mechanical model cross-section design was made based on the available NbTi Rutherford-type cable (Table I). A S2 fiberglass sleeve with a nominal thickness of 0.1 mm was used to insulate the cable [3].

TABLE I
CABLE PARAMETERS

Strand Diameter (mm)	0.808
Number of strands	38
Cable width (mm)	15.4
Cable major thickness (mm)	1.588
Cable minor thickness (mm)	1.325

The ROXIE code [4] was used to develop a coil cross-section with an acceptable field quality and a reasonable cable block positioning. Fig. 1 shows a cross-section of the dipole coil, which consists of 38 turns grouped in 5 blocks. The conductors were aligned to the inner radius to avoid using thin shelves in the end parts.

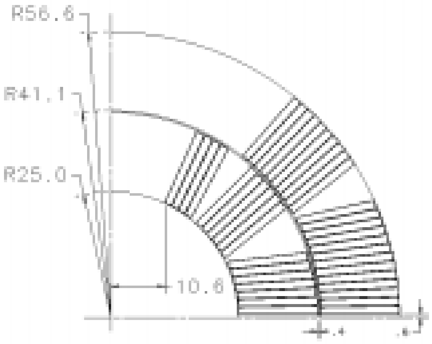

Fig. 1. Coil cross-section (measurements are in mm).

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Based on the coil design, ROXIE was used to generate an output file that contained the information necessary to fabricate the coil end parts. The details of end parts design and fabrication are discussed elsewhere [5]. The output file was transmitted electronically to LBNL for machining of the end parts using a six-axis wire EDM. 6061 T-651 aluminum alloy was used for the end parts fabrication. Quality control at FNAL was provided using a Coordinate Measuring Machine which showed that the fabricated end-parts were well within the tolerances provided (± 0.2 mm). Fig. 2 shows a set of the inner and outer layer coil end parts for one half of the magnet. The inner and outer layers were wound from the same piece of cable thus eliminating an inter-layer splice. This, however, required winding of the outer layer coil on top of a pre-wound inner layer coil.

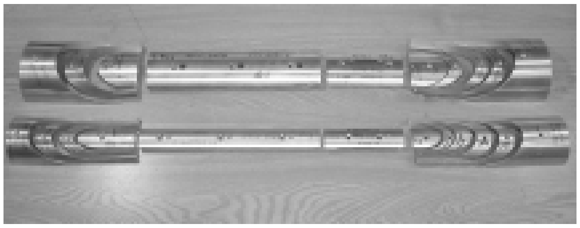

Fig. 2. End parts and pole pieces for the mechanical model.

B. Cable Insulation

A S-2 fiberglass sleeve was used to insulate the cable used in the mechanical model. S-glass is an Owen-Corning fiberglass name for AF-994 glass, which is a high tensile strength glass with superior strength retention properties at elevated temperatures (compared to E-glass). This property is particularly attractive since the reaction temperature for the Nb_3Sn coils can run as high as 700 C.

The fiberglass sleeve obtained from a manufacturer usually has an organic starch/oil based binder which is used to keep the individual fibers of glass together to form a continuous thread. During the reaction cycle, this binder would disintegrate leaving free carbon that could potentially be a problem because the coil structure could acquire transverse conductivity. Therefore, one must remove this organic binder and replace it (to get strength needed for insulation) with a new one (such as palmitic acid) that would not leave solid carbon after the heat treatment. Although, it was not very difficult to put the insulating sleeve on the cable without the application of this replacement binder, the procedure worked badly for a practice coil. The cable insulation was weak and left few holes. Further it was difficult to handle the cable without damaging the insulation. To have a reference point for future experience, it was decided not to remove the sizing from the sleeve insulation for the mechanical model coils.

C. Coil Winding

The winding table available at FNAL Technical Division was modified to wind the mechanical model coils. A simple winding mandrel and a set of fixing clamps were designed and fabricated for the coil winding. To start winding, a layer-to-layer transition was made, and the insulated cable was clamped to a specially designed transition part. After winding each coil block in the first layer, the corresponding end parts were fixed to the winding mandrel at their nominal position using dowel pins and socket-head shoulder screws. One of the main concerns during the end parts installation was the possibility of damaging the cable insulation by the sharp edges of the end parts. Although, some precautions were taken like using a Kapton tape to prevent the insulation damage, and rounding the sharp edges of the end parts, the first coil had some defects due to the cutting and pinching of the insulation when the end parts were forced to their final axial positions. Some wearing of the insulation was also observed under the clamps because the coil was forced into its radial position several times during winding.

After the first layer was wound, it was formed using a forming fixture and an S2 glass tape bandage was applied to fix the coil shape. The end parts of the second (outer) layer were attached to the mandrel through the first layer end part holes with socket-head shoulder screws. In addition, dowel pins were used to hold the two layers of end parts together and to keep the alignment after the shoulder screws were removed. Once the second layer was wound, it was also fixed with an S2 glass tape bandage. Fig. 3 shows the first half of the coil before applying the second S2 glass bandage.

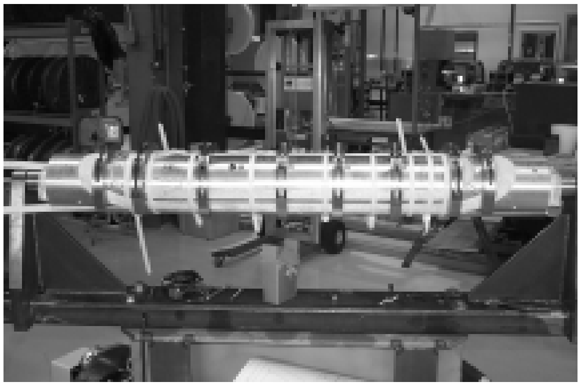

Fig. 3. First half of the wound coil.

After the first half of the coil was wound, a ceramic matrix (CTD-1002x) developed by CTD was applied and then cured at 150 °C for about 1 hour on the winding mandrel, enclosed in a curing fixture. Then the outer layer bandage was removed and the inner layer bandage was cut off at the coil mid-plane. The idea to use the ceramic binder and cure the coil to a pre-defined shape worked very well. We were able to obtain well-formed cable blocks that did not fall apart after they were released from the curing mold. The cured coil kept its shape without any additional support. As a result, we got a stiff coil structure with an outer surface that was a reflection of the curing mold surface. This important feature has made it possible to assemble the two half coils in a reaction fixture for heat-treatment and then place them together into a mold for epoxy impregnation and curing. Fig. 4 shows the first two-layer half-coil after it was removed from the curing fixture.

While winding the second two-layer half-coil, some changes were made to the cable insulation scheme to explore the options provided by the ceramic matrix. After the insulating sleeve was put onto the cable, a ceramic matrix was applied and the cable was cured at 150 °C for about 1 hour. This procedure changed the insulation thickness from the nominal value of 0.1 mm to about 0.2 mm, which forced us to adjust the number of turns per block in the coil cross-section to be able to use the existing end parts. Although the coil end quality was sacrificed, the cable insulation appeared to be much stronger than in the first half-coil. The insulated cable could easily withstand the tension applied by the winding tooling, and even a slight hammering to force the turns in nominal position did not damage it. There were no turn to turn shorts during the second half-coil winding, unlike during the first half-coil winding. Moreover, after curing, the second half-coil passed successfully a 1000 V ring test and a 1000 V High-Pot coil-to-ground test.

Fig. 4. First half of the cured coil.

D. Reaction and Epoxy Impregnation

The two half-coils were assembled together in a reaction mold and heat-treated at 450 °C for about 8 hours. Since the end parts of the mechanical model were made of aluminum alloy and the coils were wound using a NbTi cable, the standard Nb_3Sn reaction cycle with a maximum temperature of 650°C was not used at this step. During this reaction cycle, the ceramic binder became porous due to volume shrinkage which turned out to be beneficial in terms of the epoxy penetration [6]. The reacted coils were then placed in a mold and vacuum impregnated with a low viscosity, long pot-life epoxy, CTD-101K. The impregnation procedure has been described in detail elsewhere [7]. Fig. 5 shows a photograph of the coil after it was removed from the impregnation and curing mold.

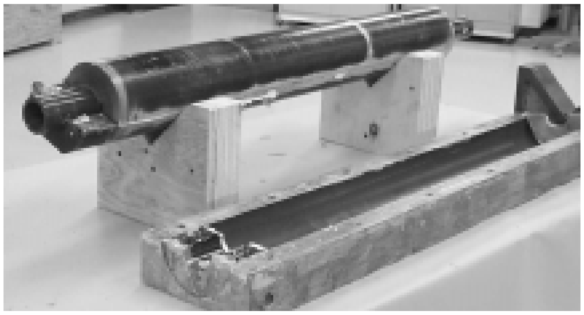

Fig. 5. Mechanical model after epoxy impregnation.

III. TEST RESULTS

The impregnated coil structure was subjected to mechanical and electrical tests that could show us possible down sides of the chosen assembly technique. First of all, the geometrical characteristics were measured to check the coil diameter, eccentricity, and straightness. The coil diameter and straightness reflect the curing mold surface. To save design and fabrication costs and the manufacturing time, this time we did not require a high precision machining of the curing mold surface. This resulted in some variation in the outer diameter of the impregnated coil.

A High-Pot test performed with the impregnated coil showed coil to ground shorts. To investigate the cause of these shorts and to check the quality of epoxy impregnation, the mechanical model was sectioned transversely at several locations along the length of the model. Fig. 6 shows a representative photograph of the cross-section of the mechanical model. The top half-coil corresponds to the nominal cross-section, while the bottom one has reduced number of turns due to the thicker insulation.

Fig. 6. Mechanical model cross-section.

A. Cross-Section Analysis

The overall impregnation quality was observed to be good and no voids were seen. Each cable had a visible insulation layer around it, which showed that the cable insulation in the straight section was not damaged. A further microscopic examination of the cross-section was performed to investigate the quality of epoxy impregnation and also to measure the insulation thickness. It was observed that the epoxy had penetrated into each cable block and even filled the spaces in between the rows of strands. Fig. 7 shows a micrograph of the cross-section centered about the midplane. The two conductors above the midplane belong to the second half-coil with a thicker cable insulation due to the application of the ceramic matrix to the insulation before winding. The two conductors below the mid-plane are from the first half-coil with the nominal cable insulation. The insulation thickness was measured under a microscope for both halves of the mechanical model. The average thickness of the insulation on the thin and thick insulation sides was 115 μm and 188 μm respectively. There was not much variation in the insulation thickness along the width of the cable in the straight section.

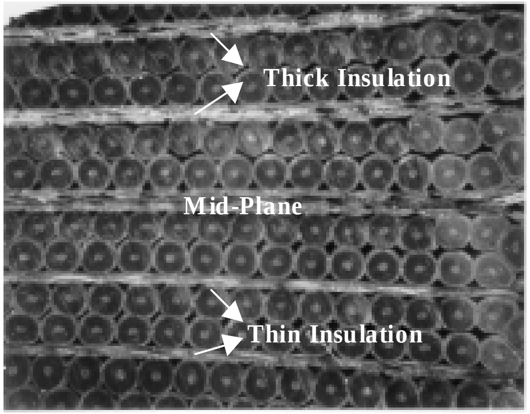

Fig. 7. Micrograph of the coil cross-section.

B. End Analysis

The lead and the return ends of the mechanical model were also sectioned to study the quality of epoxy impregnation and the cable block positioning. Except at few spots, the impregnation quality was quite good. The spots without epoxy were found in the vicinity of regions where a ceramic putty was used to fill up the space on the outer surface of the conductor group (note that the conductors were aligned to the inside surface). The epoxy did not penetrate through the ceramic putty at these locations because of the low temperature used for the reaction. As a result, the crystallization of the ceramic putty did not occur fully and hence the putty was not porous.

A closer investigation of the ends revealed that the cable insulation to the ground (inner steel pipe) was damaged in this region, so a short circuit from the coil to ground was inevitable. Such a damage in the coil insulation was observed at few other locations at both ends. The reason for this insulation damage could probably be the application of a rather large pressure to the cable blocks during the impregnation process, when the insulation is already weakened after thermal treatment of the coil. To understand this process, several cuts were made to find the location where the cable block alignment pattern changes to the outer surface to be able to transfer the radial force from the outer layer to the inner layer. This location was found to be close to the section where the end part starts its transformation into a straight section.

IV. SUMMARY

A two-layer cos(θ) mechanical model has been fabricated and studied at Fermilab as a first step towards the fabrication and testing of short Nb_3Sn dipole models. It was observed that the mechanical properties of the cable insulation could be improved significantly if the ceramic binder is applied prior to winding [8]. This promises to simplify the coil winding procedure and make the coils reliable, which is very important for the mass production of the dipole magnets. The epoxy impregnation procedure worked out well. The tooling, however, needs to be improved to meet tighter tolerance requirements.

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