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A. Lipski, R. Bossert, J. Brandt, J. Hoffman,
G. Kobliska and J. Zweibohmer

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

W. Higinbotham, R. Shields and R. Sims

Superconducting Super Collider Laboratory
2550 Beckleymeade Avenue, Dallas, Texas 75237

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ALTERNATE MANUFACTURING PROCESSES AND MATERIALS FOR THE SSC DIPOLE MAGNET COIL END PARTS

Arie Lipski, Rodger Bossert, Jeffrey Brandt,
Jay Hoffman, Gregory Kobliska,
and John Zweibohmer

Fermi National Accelerator Laboratory*
Box 500
Batavia, IL 60510

William Higinbotham, Robert Shields,
and Richard Sims

Superconducting Super Collider Laboratory
2550 Beckleymeade Avenue
Dallas, Texas 75237

ABSTRACT

Modern magnet designs such as the SSC dipole utilize smaller bore diameter and wider superconducting cable. Challenging winding techniques place greater emphasis on the role of the coil end parts. Their complex configuration is derived from their function of confining the conductors to a consistent given shape and location.

Present end parts, made of G-10 composite, are manufactured utilizing complex and expensive 5-axis machining techniques. Several alternate manufacturing processes and materials described in this paper will result in a substantial cost reduction for mass producing the end parts.

The alternate processes are divided into two major groups. The composite group consists of Resin Transfer Molding (RTM), Compound Transfer Mold (CTM), Injection Molded Composite (IMC) and Compression Molded Composite (CMC). The base metal coated group consists of Chemical Vapor Deposition (CVD) dip coating and hard coatings/anodizing. The paper will provide an overview of the various processes and compare test performance and cost to that of the process currently used.

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INTRODUCTION

The magnetic field pattern in a superconducting coil is governed by the arrangement of the current conductors, thus making the precise coil geometry and location of utmost importance. This precision must be maintained in spite of the large Lorentz forces acting on the current conductors.

In modern magnet designs such as the SSC dipole, which utilizes small bore diameter and wider superconductors, cables are subjected to high internal stresses while being wound around the end part. End parts are designed to confine the conductors to a predetermined position in the cold mass coil assembly (Figure 1). The unique shape of the end parts was developed to create lower stress paths for the cables, making them easier to wind. This shape must be well defined to both the part manufacturers and those analyzing the magnetic field.

End parts used in SSC prototype dipole magnets are made of G-10 CR composite and manufactured using complex and expensive 5-axis machining techniques.

This paper will describe and summarize a two year program at Fermilab to develop processes and materials to replace those currently used.

The objective of the program was to achieve a substantial cost reduction (50% or better) without compromising quality or performance.

The development program was divided into two main groups:

- Molding of organic materials
  a. Resin transfer molding (RTM)
  b. Compound transfer molding (CTM)
  c. Injection molding composite (IMC)
  d. Compression molded composite (CMC)

- Coating of cast metals
  a. Hard coating/anodizing
  b. Dip coating
  c. Chemical vapor deposition (CVD)

While satisfying the mechanical requirements is an important criteria, withstanding the operating and environmental conditions became the limiting factor in the material selection process.

Compressive and flexural strength are crucial for sustaining the loads exerted on the end parts during the curing and collaring processes as well as the Lorentz forces during operation. Flexural modulus, however, should be kept low to allow some flexibility during coil winding.

While strength and modulus may not be the governing factors in selecting the proper coating and metal base material, good electrical insulator properties and the mismatch between the base material and the coating are the limiting criteria.

It is desirable that the coefficient of thermal expansion of the chosen material for end parts will be close to that of the coils so that the assembly as a whole will respond to changes in temperature in a uniform manner.

Since data on radiation-resistant polymers is limited, and performing radiation testing is expensive, it was decided to initially target materials with published radiation resistance data. While it is understood that the base metal used for the coated end parts should be non-magnetic, the coating should resist abrasion and wear.

The qualified material for the end parts will have to meet the following physical properties:

- Compressive strength - 172 MPa
- Flexural strength - 206 MPa
- Coefficient of thermal expansion (CTE) 10.0 to 20.0 x 10^{-6} m/m/K approximately .004 m/m between 300 and 4K.
- Sustain an electrical potential as high as 4000 volts.

The above physical properties are expected to be maintained through a temperature range of 4 to 523K and radiation level of 1.0 x 10^9 rads (10 MGray)

The short duration, high temperature requirement is mainly to accommodate the curing of the high temperature Kapton insulation being promoted by Brookhaven National Laboratory. Fermilab coils are cured at 135°C. Since it is not clear that high temperature curing is essential, the high end temperature requirement could possibly be relaxed to the FNAL level.

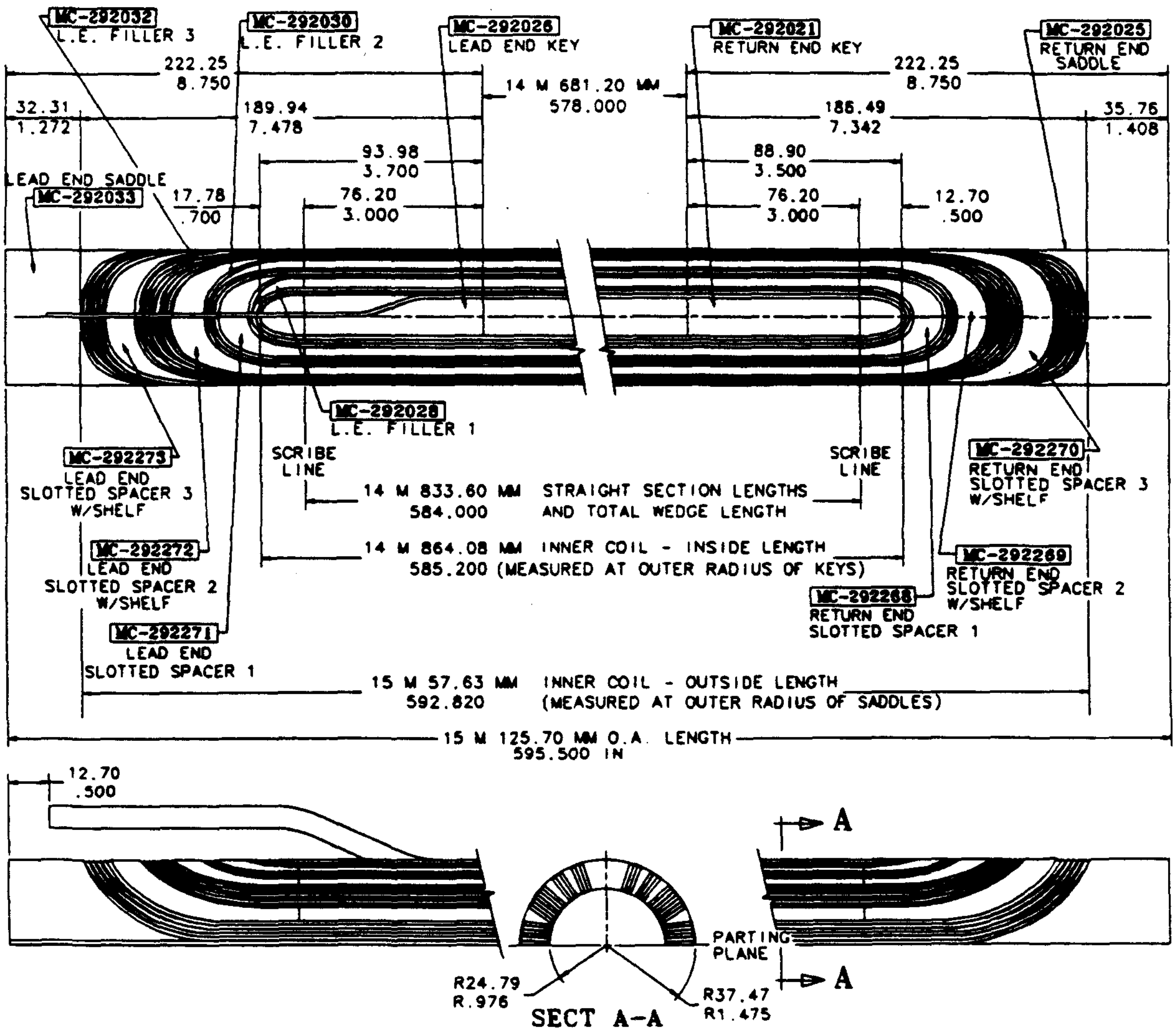

Figure 1. SSC 50mm cold mass inner coil assembly

RESIN TRANSFER MOLDING (RTM) AND COMPOUND TRANSFER MOLDING (CTM)

Resin Transfer Molding (RTM) is a closed mold process wherein dry reinforcements within the mold are injected with a filled catalyzed low viscosity resin. Vacuum is applied to minimize the amount of trapped air and cure occurs at room temperature. The dry reinforcement (preform) is composed of long (continuous) fibers held together in some textile fashion such as weaving, braiding or plies of glass stitched and glued. The fiber orientation is dictated by the design requirements of the part and can vary from one end of the part to the other.

Compound Transfer Molding (CTM) is a modified form of conventional filled molding compound injection. Using the same mold as for the RTM, a compound containing chopped glass (1.5 mm long E-glass fibers) is injected into the cavity. Thin cross sectioned areas, where the molding compound would not provide satisfactory strength, are reinforced using continuous fiber plies. Though structurally superior, parts made by RTM process are more labor intensive and thus more costly than those made by CTM process.

A two part development program intended to explore the feasibility of applying RTM and CTM processes to produce end parts was completed by Spaulding Composites Company in August 1991. Two parts, the inner coil assembly return end key and saddle (Figure 2 and 3), were produced in both processes using three different resin systems.

After successfully using Dow Tactix 123 epoxy resin with Tactix curing agents in the first part of the program, resins which satisfy most of the performance criteria were used in the second part. Those resins were:

- CTD-101 - Anhydride cured epoxy DGEBA based (400 cp; 60 hours pot life at 40°C processing temperature)
- CTD-102 - Anhydride cured epoxy NOVOLAC based (450 cp: 50 hours pot life at 40°C processing temperature)

These two resin systems developed by Composite Technology Development (CTD) have been tested for performance in cryogenic and radioactive environments with good results.[1]

The reinforcement used for the RTM parts was E-glass identical in content and weave to the glass used in G-10 CR.[a] A webbed binder was applied between the plies during the preforming process to give the preform sufficient stability for handling and cutting.

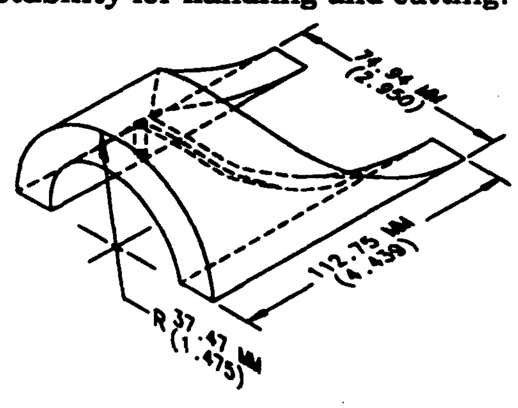

Figure 2. SSC 50mm dipole cold mass inner coil return end saddle

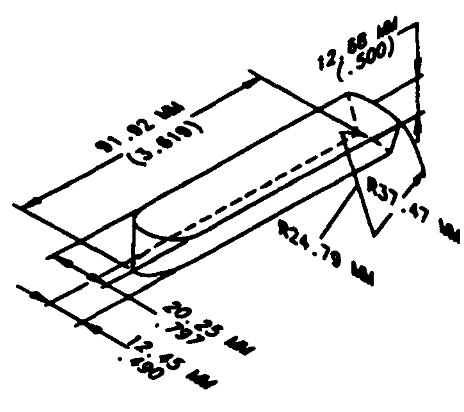

Figure 3. SSC 50mm dipole cold mass inner coil return end key

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[a] 28-T glass from BGF Industries

Thin cross-sections such as the saddle "legs" which taper to approximately 0.13 mm thickness require additional reinforcement. Since this gap is too small for the CTM molding compound to reach, a strip of E-glass cloth was laid in along the saddle's "base" to provide the reinforcement. This prepositioning of reinforcement process can be applied to both the RTM or the CTM methods. (See figure 4)

There is a difference in the method of filling the mold cavity between Tactix and the CTD resins for both the RTM and the CTM processes. While pressure was applied when using the Tactix resin, vacuum only was used to draw the CTD resins into the mold cavity. The extended fill time helped any residual air trapped in the resin to escape through the vacuum, thus improving the surface quality of the parts.

INJECTION MOLDING COMPOSITES (IMC)

Three different thermoplastics which satisfy most of the material performance criteria were selected.

- Amoco Torlon 5030 - 30% glass fiber poly(amide-imide)
- Green Tweed - Arlon[b] 1160 - 30% glass fiber - polyetheretherketone (PEEK)
- Green Tweed - Polyetherketone (PEK) - 30% glass fiber

Both PEEK and PEK have the same chemical structure with the difference being in the ratio between ether and ketone. PEK has better resistance to high temperatures due to its higher glass transition temperature. As evidenced by Figure 5, some of the end part configurations can get rather challenging for molding, in particular for high temperature high pressure polymers like the PEEK and Torlon. At this stage of the development it was decided to test machined parts out of injection molded tubes and avoid the high expense of molds. Five different inner coil return end parts of each material were machined.

COMPRESSION MOLDED COMPOSITES (CMC)

As opposed to RTM which is a closed mold process, in compression molding the mold is open when the material is introduced. The material is shaped by the closing pressure and by heat.

Three sets of compression molds for inner coil return end saddle, key and spacer (Figures 2, 3 and 5) have been produced to study the process using various materials. Two different composite compounds were molded:

- Ciba-Geigy - "Green putty"[c]
- Emerson Coming - "Blue" stycasted[d]

Both materials are highly filled epoxies that have been used in accelerators but are too brittle to be used as end parts. These materials were selected

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b) Trade name with similar properties to those of ICI Victrex GL30

c) AV 1580 resin amine + HV 1580 hardener

d) 2850 FT filled resin and hardener

Table 1. Flexural Strength and CTE Test Results

	Machined	RTM	Injection Mold	
	G-10	CTD-101	Torlon	PEEK
Flexural Strength* (MPa)	482.0	413.2	338	233
Coefficient of thermal contraction 10^{-5} m/m/K	1.15**	1.21**	1.62***	2.20***

* At room temperature
** Between room temperature to 77K
*** Between room temperature to 422K

Flexural test values were compared between machined G-10CR, RTM, CTM and injection molded processes at room temperature. The CTE test, however, was measured only for parts produced in RTM and CTM processes and was compared to vendors data for the injection molding process (Table 1).

For the insulation breakdown test[2,3] a Hi-Pot tester was connected between a coil lead and the coated key. Breakdown was determined when the leakage current rose rapidly above a set value. Voltage was then turned off and reapplied for the second breakdown reading.

To evaluate performance of the end part material and process in production and operation, parts are incorporated into coil assemblies and later placed in a test magnet. After a visual and dimensional inspection parts are wound and cured (138 MPa and 135°C) into a coil assembly. The ends get separated from the coil assembly, potted and sectioned (Figure 6). The sectioned surfaces are surveyed and results are compared to the nominal design dimensions. The parts get inspected also for material failure or deterioration.

Coil assemblies containing acceptable parts which warrant further evaluation may be placed in test magnets. These magnets are subjected to complete cryogenic and electrical testing which simulate operating conditions with the absence of beam.

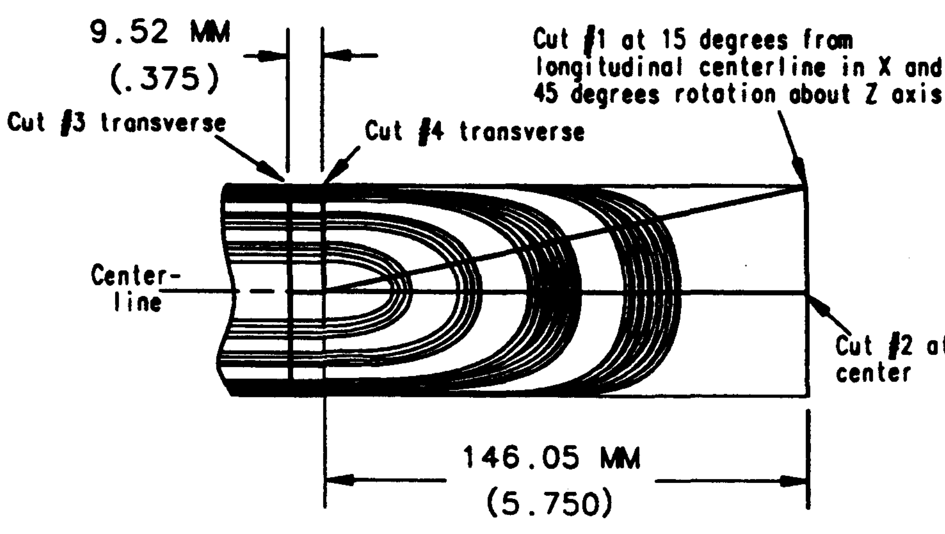

Figure 6. Sectioning of return end inner coil end

Eleven coil assemblies have been completed to date containing various combinations of end parts produced by the different processes.

Specifically, RTM return end saddles and keys using CTD-101, Torlon and PEEK return end parts machined out of injection molded tubes and coated aluminum return end keys have all survived the winding and curing process. However, it was determined that an adhesive other than the one presently used for the G-10CR end parts should be used with the Torlon and PEEK parts. Only RTM return end saddles and keys which were produced in the first part of our development program (using Tactix 123 resin) have been tested in a test magnet. Those parts tested successfully with similar tests scheduled in the near future for the RTM parts produced in the second part of the program (using CTD-101 resin).

CONCLUSION

At the start of this development program the base line performance criteria was that of the machined G-10 CR end parts. At the present time, due to changes made in the requirements, the baseline design was changed by General Dynamics to machined Spaulrad. Issues of higher radiation levels, elevated curing temperatures, and requirement for stronger keys had to be addressed in addition to the main objective of reducing cost.

Performance of RTM parts in coil assemblies and in test magnet as well as results of the flexural test, indicates that this process can produce the strength required from end parts. Using the CTD-101 resin system gives assurances to its ability to perform in cryogenic temperatures as well as high levels of radiation. Temperatures above Fermilab curing temperature (135C°), however, could present a problem using this resin system. Further development of the preform production in addition to improving of parts quality and process reliability are still necessary.

Injection molding on the other hand offers a less expensive alternative when compared with the RTM process. However, the strength of molded end parts may prove to be insufficient. It is crucial to produce a set of molds and parts which can be tested. This will also aid in understanding the challenges involved when molding with materials like Torlon and PEEK (or PEK).

Though it may offer the required strength and moderately priced parts, the compression molding process needs to be further studied and investigated. The use of crushed Spaulrad is presently being studied by Spaulding Composites and General Dynamics.

Metal coating can offer the added strength required in particular from the return end keys during curing. Though finding a coating which will satisfy all the requirements may require some research, it should be further explored.

As can be seen from the cost comparison in Table 2, the methods discussed in this paper can offer a cost reduction when compared with machined end parts.

Table 2. Cost Comparison for Return End Saddles - Machined Versus Other Processes (for 10,000)

Machined (Material & Labor)	RTM CTD-101	RTM CryoRad	CTM CTD-101	Injection Torlon	Injection PEEK
$150	$51.0	$205.0	$31.0	$11.0*	$37.0*
Tooling:	$58,500	$54,000	$45,000	$23,000*	$12,000*

* These prices are for 40 mm end parts and are about 1 year old.

ACKNOWLEDGMENTS

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