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Using Additive Manufacturing technologies in high-field accelerator magnet coils

I Novitski[1], J Coghill[1], T Beale[1], J Bergeron[2], R Davidoff[2], B Oshinowo[1], S Raje[2], D Swanson[1], C Wilson[1], AV Zlobin[1]

[1] Fermi National Accelerator Laboratory, Batavia, IL 60510, USA
[2] GE Additive, West Chester, OH 45069, USA

Abstract. Recent advances with Additive Manufacturing technologies using various materials allow them to be considered for the manufacture of precise and complicated metal parts of the magnet coils of high field accelerator magnets from aluminum bronze, titanium alloy, stainless steel, etc. The 3D printing technology is being also used to fabricate prototype models of real parts to test and optimize their geometry. This paper discusses the designs of the complex stress-management coil parts developed at Fermilab, their fabrication using Additive Manufacturing technologies, and quality control methods and results.

1. Introduction

Superconducting (SC) dipole and quadrupole magnets are key elements of charged particle accelerators. A strong magnetic field with a good field quality in the aperture is required for a stable trajectory of particle beams. SC magnets based on Nb-Ti superconductor with the nominal magnetic fields up to 7-8 T were developed and used in the circular colliders such as Tevatron, HERA, RHIC, LHC [1]. An interest to accelerator magnets with higher field continues. SC magnets with magnetic fields up to 11-12 T have been developed during past two decades and are now being produced for the LHC luminosity upgrade [2]. Modern concepts of a Future Circular Collider (FCC) for High Energy Physics push the operation field of SC magnets even higher to a level of 16-20 T. This level of magnetic field requires using advanced low-temperature and high-temperature superconductors and new magnet technologies.

Most of the present SC accelerator magnets are based on multi strand Rutherford cables, made of round composite wires, and cos-theta coil geometry. Composite round wires, compatible with Rutherford cable technology, are produced by industry based on low-temperature Nb_3Sn and high-temperature Bi2212 class superconductors. Both materials are brittle and, thus, require using React-&-Wind technology with multistep high-temperature heat treatment after coil winding.

Wind-&-React coil technology for both superconductors is being extensively developed for the last two decades. It was found that Nb_3Sn composite wires, which use Cu matrix, need ~10 days of complex heat treatment at maximum temperatures close to 700^{o}C in Argon atmosphere to form superconducting phase with optimal structure to achieve the best critical current density. Bi2212 composite wires use Ag matrix and to achieve the best critical current density require a multistage HT in a highly corrosive Oxygen atmosphere at 50 bar pressure with maximum temperatures up to 900^{o}C for ~2 days. The high-temperature heat treatments call for metallic coil part and insulating materials which can withstand the high temperatures. After HT all the coils are usually impregnated with epoxy for providing turn mechanical integrity in coil and reinforcing their electrical insulation. The impregnated coils work in temperature range of 300-4 K under cycling pressure up to ~150 MPa.

Coils made of the stress/strain sensitive superconductors and operating at high magnetic fields must withstand very high electromagnetic forces at cryogenic temperatures. To provide a stable turn position and to keep the strain/stress in coil within an acceptable range for the superconductor during magnet fabrication and operation, various stress management coil structures have been proposed and are being studied. These structures have complex 3D geometries that are difficult to produce using traditional fabrication tools, and rather tight tolerance requirements. Recent advances with Additive Manufacturing (AM) technologies using various materials allow them to be considered for fabrication of precise and complicated metallic parts used in the magnet coils of high field accelerators from aluminum bronze, titanium alloy, stainless steel, etc. Additionally, AM is being also used for rapid prototyping of parts using inexpensive plastic materials to support design iterations aimed at optimizing part geometry for functionality.

This paper discusses the designs of the complex coil parts developed at Fermilab, their fabrication using AM technologies, quality control methods and the results.

2. Cos-theta coils for high field magnets at Fermilab

Cross-sections of superconducting dipole coils developed at Fermilab based on cos-theta geometry are shown in Figure 1. High currents and strong magnetic fields in coils produce large electromagnetic forces which can degrade or even damage brittle superconductors. These forces significantly increase with the level of magnetic field and magnet aperture and at some level needs special treatment. Stress Management (SM) concept being developed at Fermilab introduces rigid elements into the cos-theta coil structure to mechanically protect brittle superconductor. In large-aperture coils shown in Figure 1 c) and d) each coil block is placed in its own compartment and supported separately. As a result, azimuthal and radial components of the electromagnetic force applied to coil blocks are not accumulated but transmitted to the coil and magnet structures bypassing coil blocks.

The two-layer regular coils (in Figure 1 a, b, and d) have three blocks separated by two wedges in layer 1 and two blocks and one wedge in layer 2. Each layer of the large-aperture SM coils (c and in Figure 1) is split into five blocks, separated by 5 mm wide spacers, with the number of turns approximately following the cos-theta distribution. In addition, the SM coil layers are separated by 5 mm in the radial direction from the inner coil and from each other to provide space for the support structure.

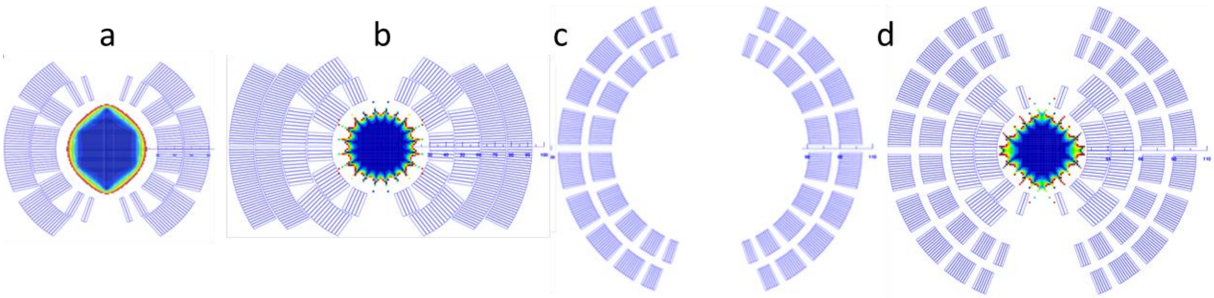

Figure 1. Cross-sections of superconducting dipole coils based on cos-theta geometry developed at Fermilab: a) 60-mm aperture 2-layer coil for 11 T dipole (MBH) for the LHC upgrade [3]; b) 60-mm aperture 4-layer graded coil used in 15 T dipole (MDPCT1) [4]; c) 120-mm aperture 2-layer coil with stress management developed for 11 T dipole [5]; and d) 60-mm 4-layer graded coil with stress management outer layers for 17 T dipole [6]. The cross-section of the inner coil was optimized for best field quality using ROXIE code [7] and considering the field harmonics produced by the outer coil. The magnetic model included a cylindrical iron yoke with an outer diameter of 600 mm.

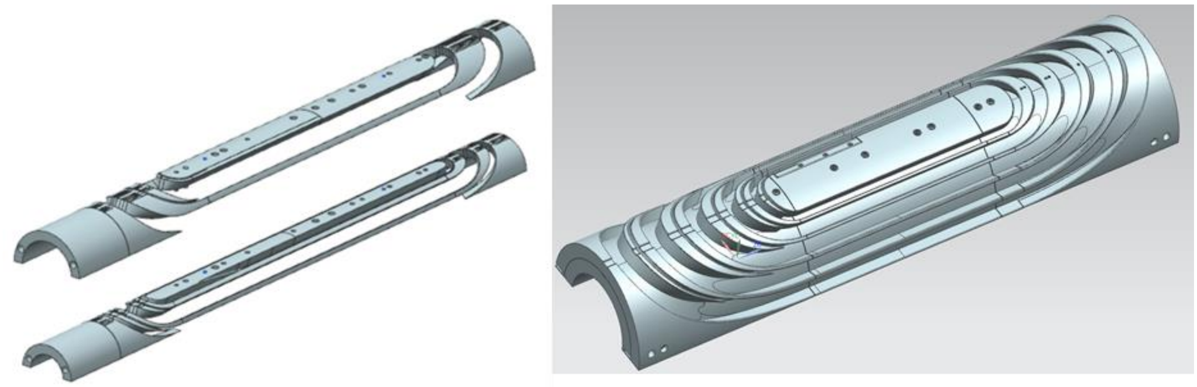

Figure 2. 3D parts of the two-layer cos-theta coils without (left) and with stress management (right). The left and right sides of each figure correspond to the lead and return ends respectively.

Figure 3. Practice end parts used in various cos-theta dipole coils: a) SLS end spacers; b) waterjet end spacer; c) plastic end spacers; and d) plastic parts for stress management coils.

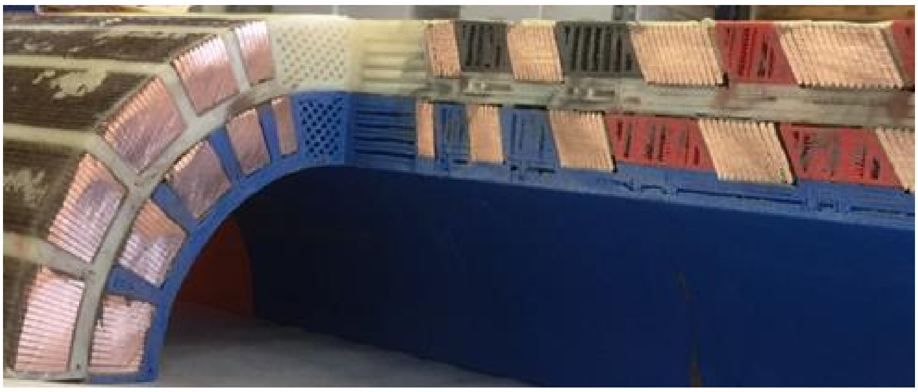

Figure 4. Two-layer SMCT practice coil with axial and transverse cuts of return end.

3. Cos-theta coil part design and fabrication

3.1. End part design and prototyping

Coil ends are 3D regions with complicated cable deformations including bending and twisting. Coil end design has to minimize distortion of the integrated field and limited peak field enhancement, produce compact and friendly for Rutherford cable winding with minimal stress, use of metallic end parts, and limits conductors motion to avoid quench in SM concept. At Fermilab all the coil ends and end parts are designed using the BEND program [8]. The program creates the conductor surfaces and groups based on the minimization of strain energy accumulated within the cable. It generates also spacers suitable for fabrication without coil gaps. A similar purpose programs were developed at other labs, e.g. 3D ROXIE [7] at CERN, analytic codes at CEA-Saclay [9], etc.

3D parts of the 60-mm aperture two-layer inner cos-theta coil without stress management and the 120-mm aperture two-layer outer cos-theta coil with stress management are shown in Figure 2. The left and right sides of each figure correspond to the lead and return ends respectively.

Due to the high complexity of end part geometry and the large variation of cable mechanical rigidity, end parts used in superconducting coils for accelerator magnets need prototyping and their qualification in practice windings. The use of AM for parts prototyping increases their design quality and reduces the time and cost of the parts development. Several AM technologies are being used to fabricate complicated coil end parts for the practice windings to finalize part design such as selective laser sintering (SLS), electric discharge machining (EDM), 5-axis waterjet machining, and 3D printing using carbon fiber ABS (Acrylonitrile butadiene styrene). Examples of parts produced using the above technologies are shown in Figure 3.

Coil practice winding validates interfaces of end parts with adjacent coil turns. All plastic parts were printed at Fermilab using Stratasys F170 FDM printer and corresponding CAD models. It allows verifying the part design before procurement, checking important production steps, testing tooling. In the case of SMCT coils, practice winding permits also learning new procedures of cable winding into slots, checking cable rigidity during winding, and confirming parts sizes, cable positioning, room for cable expansion for reaction, etc. A 3D view of practice coil return end with axial and transverse cuts is shown in Figure 4 confirming optimal turn position and minimal gaps inside coil winding.

3.2. Printing of cos-theta coil end spacers

AM is very attractive technology to produce metallic parts with complex 3D geometries. One type of AM process, used in manufacturing of metal parts, is called Laser-Powder Bed Fusion (L-PBF). This process uses a laser to melt layer by layer the powdered material feedstock and to produce a consolidated metal part of a desired shape. A melt pool is generated by the laser, which plays a crucial role in the quality of the final part in terms of surface quality, part geometry, and material properties. The characteristics of that melt pool are developed and controlled by the parameters used by the L-PBF machine, and can include laser power, spot size, speed, offsets, and spacing. Additionally, best practices in Design for Additive Manufacturing (DFAM) are also required to ensure success. One of the key DFAM principles used to manufacture parts with L-PBF is support structure, and it can serve 2 purposes. It can be used to dissipate heat away from the melt pool to ensure proper cooling rates, and it can act as a physical anchor to withstand thermal gradients created by the melt pool. The proper dissipation of heat away from the melt pool and inclusion of physical anchors into the part build layout ensures conformance to surface quality, mechanical property, and part geometry requirements. Examples of such support structure can be seen on the left photo in Figure 5.

L-PBF processes can use weldable powdered materials, such as 316L, Ti6Al4V, Nickel Alloys, Aluminums, and Copper alloys. The mechanical properties of L-PBF parts are typically higher than cast and comparable with those of solid materials [13]. At cryogenic temperatures the printed materials still have better tensile characteristics but with compromised ductility [14]. A layering and discretization of the melted zones has big influence on the build properties. As the melt pool moves in the build plane, the localized heating and cooling of material results in a residual stress buildup inside the part. Therefore, L-PBF parts required a stress relief process to relieve the residual stresses. Additional heat treatments can also be added to the consolidated material to achieve desired material properties. Ultimately, machine parameters, feedstock or powder quality, Design for Additive Manufacturing (DFAM) best practices, and other process controls are crucial to ensure part quality and repeatability.

Figure 5. Spacers arrangement during printing (left) and end spacers printed on the SLM 280HL System using Ti6Al4V alloy for inner coils of the 15 T dipole demonstrator [4], [15] (right).

All mentioned above are the well-known AM process features, which were counted into a conceived design, and were a reason for caution, step by step, phased use of the AM technologies. For the entire set of coil parts, a few spacers were first printed and whole set was printed later for the next coil iteration. The coil end parts were 3D printed from stainless steel 316L and Titanium alloy Ti6Al4V and provided by CERN for 11 T (MBH) [3] and 15 T dipole demonstrator (MDPCT1) [4], [15] magnets. Arrangement of coil end spacers during printing and the end spacers printed using titanium alloy Ti6Al4V for inner coils of the 15 T dipole demonstrator are shown in Figure 5. All the magnets worked successfully at cold magnet tests at Fermilab [10], [11]. Moreover, 15 T inner coils with printed spacers worked extremely well, reaching world record field without any end problems.

3.3. SMCT coil part printing

SMCT parts for coils c) and d) in Figure 1 were printed at GE Additive. GE Additive using L-PBF technology, on a Concept Laser M2 machine. The M2 features a 250×250×350 mm^3 build envelope, a dual laser configuration, and a layer thickness capability of 20 to 80 μm. Available materials include Aluminium (AlSi10Mg, AlSi7Mg), Cobalt (CoCrMo, CoCrW), Steel (316L, 17-4PH, M300), Nickel (Ni625, Ni718) and Titanium (Ti6Al4V, CP Ti, Ti6242) alloys. The machine provides exceptional surface quality, minimal porosity and mechanical properties equivalent to wrought materials.

Support structures were used in the printing of the SMCT coils in areas where the build angle (vs. horizontal build platform) was less than 45-degrees. Several build and inspect cycles were conducted to understand and compensate for any thermal distortion and feature-specific manufacturing tolerances. Two possible print orientations for the end part were considered during the build set-up phase, as shown in Figure 6. The orientation on the left shows the part's axis tilted at a 25-degree angle relative to the build plane and the orientation on the right shows the part perpendicular to the build plane. The orientation on the left is self-supporting and the orientation on the right requires support structure, per DFAM best practices. In the self-supporting orientation, the inner diameter (ID) of the part is a slightly downward facing surface, resulting in slightly rougher surface finish (vs. an upward facing surface), fewer parts in a single build, and concerns about anchoring the ends of the semi-circular components to preserve geometric accuracy of the part ID. In order to ensure the best quality surface finish and geometric accuracy on the part ID and maximize the number of parts in a single build, the vertical orientation was chosen for this project. SMCT coil parts printed as two-layer cylinders with removed surface support inside blocks and with technological surface support before removal in narrow inter block channels in LE are shown in Figure 7.

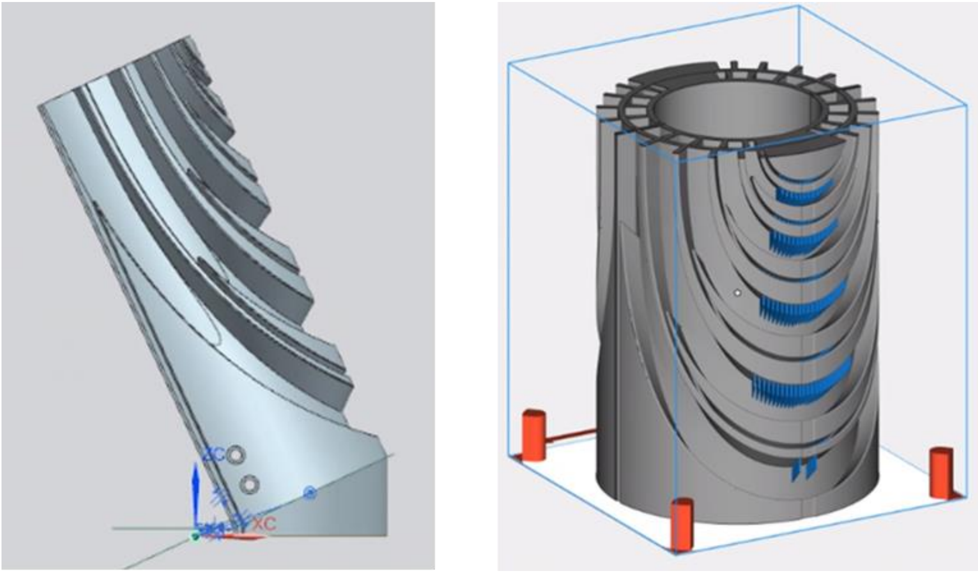

Figure 6. Two orientations of end part printing: 25-degree angle to eliminate support (left) and vertical with surface support shown in bluer (right).

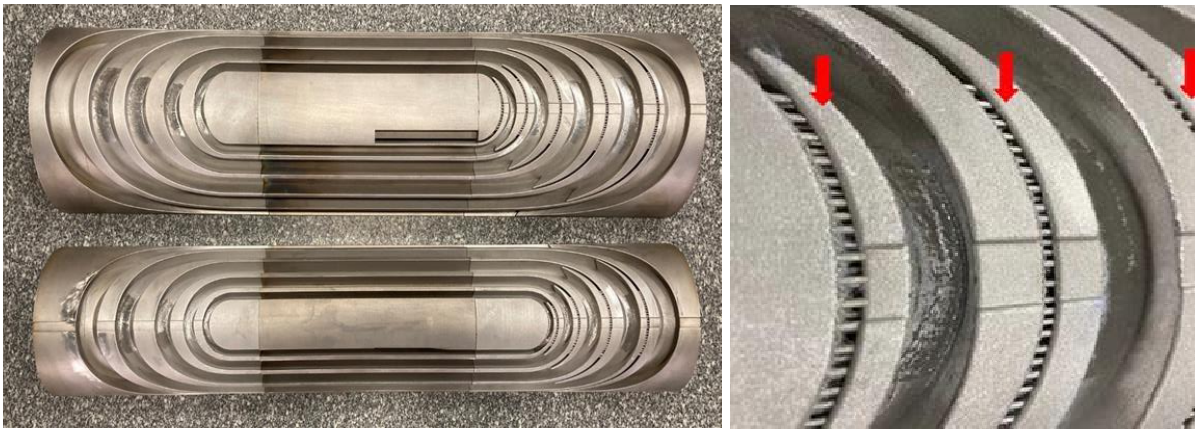

Figure 7. SMCT coil parts printed as two-layer cylinders with removed surface support inside blocks (left) and narrow inter block channels in LE with surface supports before removal (right).

4. QC inspection of coil parts

Strict tolerances to the coil part dimensions require careful size control. It is especially important for evaluating any new fabrication technology of coil parts to be used in high-field superconducting coils. The first quick size control was done using micrometer with quite encouraging results (see Figure 8). These measurements cannot be considered as completely sufficient since they do not give full information on the accuracy of part geometry. Modern advanced methods of the geometry control used at Fermilab include CMM and Laser Scanning systems.

Examples of CMM and Laser Scanning measurements of surface deviation from CAD for 3D coil end spacers and SMCT end part are shown in Figures 9 and 10. Standard CMM machines used at Fermilab allow measuring with high volumetric accuracy of 2.8 µm. Insufficient support and build rigidity lead to part small warping. The complex 3D geometry of SMCT coil parts with narrow slots and inclined surfaces made it difficult for the CMM to control their dimensions. These parts were measured by Laser Scanning system in free condition using ROMER Absolute Arm model 7525SE HP-L-20.8 external scanner.

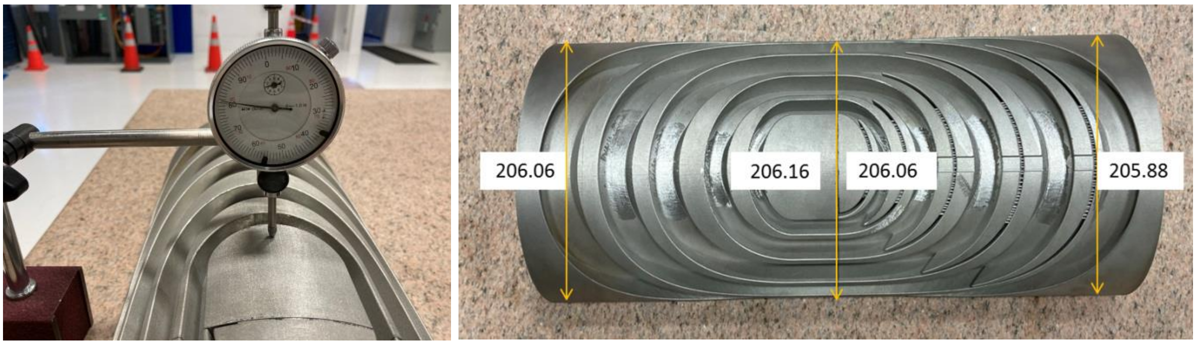

Figure 8. First control of SMCT coil end parts by micrometer on granite table. The numbers in the right picture are in mm.

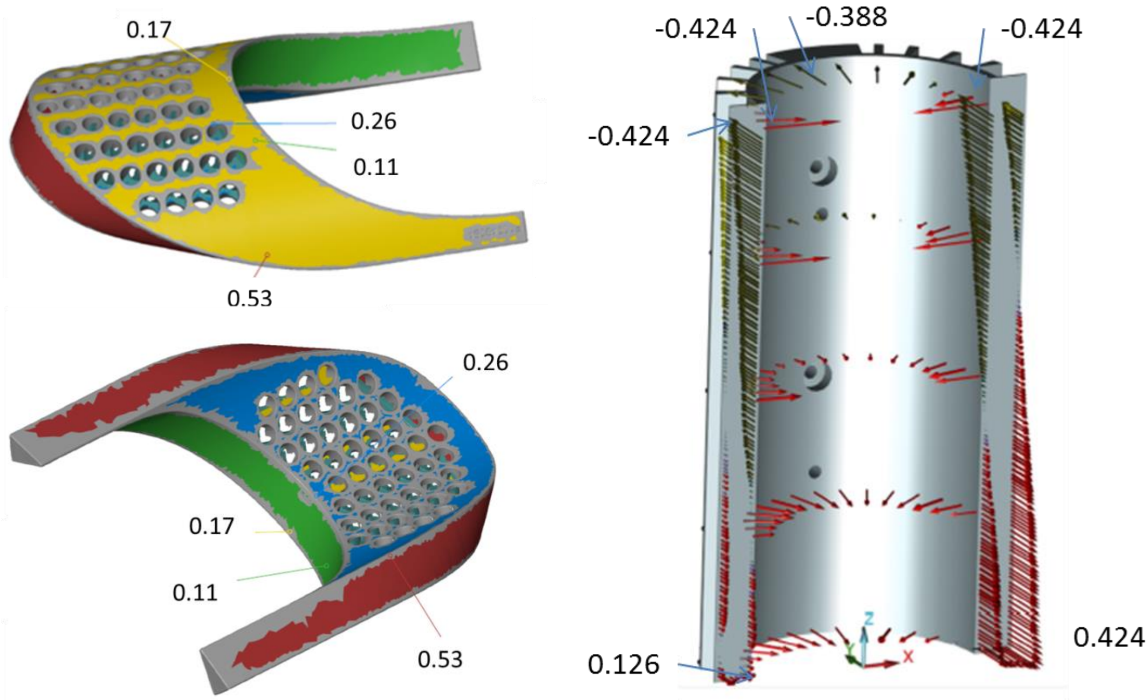

Figure 9. CMM measurements of surface deviation from CAD for 3D coil wedge (left) and straight section part of SMCT coil (right). The numbers in the pictures are in mm.

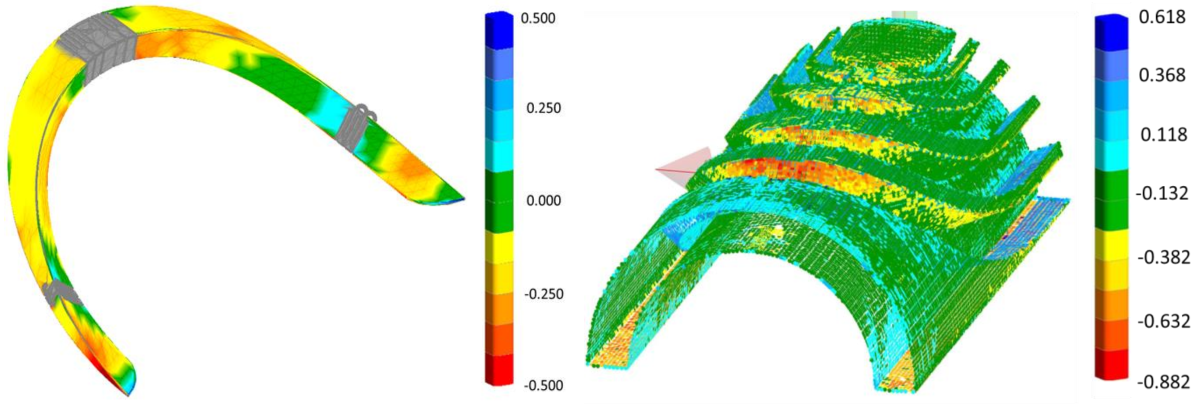

Figure 10. Laser Scanning measurements of surface deviation from CAD for 3D coil wedge (left) and return end block of SMCT coil (right). The numbers in the pictures are in mm.

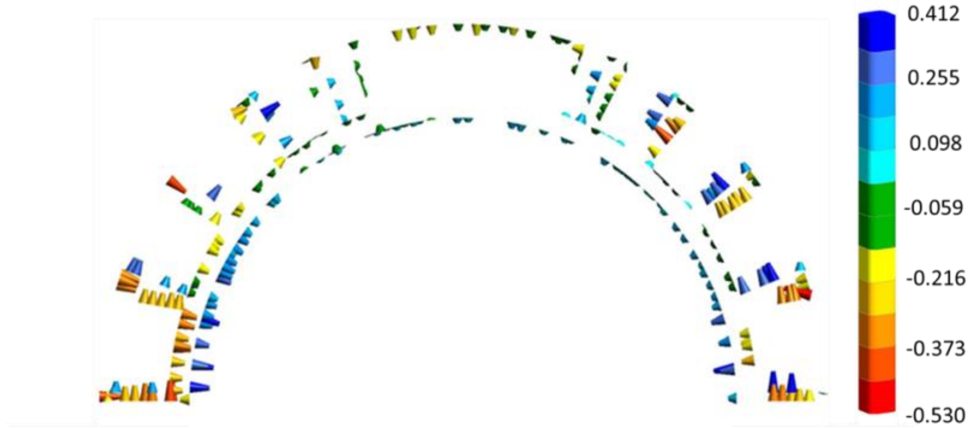

Figure 11. Measured deviations of the SMCT coil cross-section from its CAD model.

Measured part was placed on a steel table and supported by three stands. The stands were high enough that the laser scanner could measure all sides of the part. Measurements on the ceramic sphere were used to verify the accuracy of the Romer Arm external scanner. The scanning was done from one instrument location. The ROMER Absolute Arm with external Laser Scanner is paired with the New River Kinematics Spatial Analyzer^{TM} Software to collect and process the scanned data. The Full Scan data for the SMCT coil part contain 53,884,621 points. Probing accuracy for the ROMER Absolute Arm with external scanner is 27 microns and scanning accuracy to within 58 microns.

The CAD model for the part was imported into the Spatial AnalyzerTM Software and compared to the measured point clouds. A final fit to the part was done using an N-point best-fit to the CAD model with an RMS fit of about 0.2 mm. Next, the 53,884,621 point clouds were filtered to a 2-mm uniform spacing, leaving a subset of the full scan to about 63,058 point clouds. Figures 10 (right) shows a colorized deviation plot produced from this data subset. Figure 11 shows measured deviations of a cross-section of the SMCT coil from its CAD model using the same method. Best fit of cloud data points to CAD datum gives ID/OD ratio within ±0.25 mm and 3D surfaces profile within 0.5 mm. The accuracy of the SMCT coil parts is consistent with the accuracy of 3D wedges. Based on these measurements, the AM part accuracy can be considered as a good result for the first-time printing of metal objects with complicated 3D geometries and relatively high tolerance requirements. A range of measured surfaces roughness using a stylus probe Ra is within 5.5–10.5 µm. Red zones in Figure 10 corresponds to the areas of surface technological support.

5. Summary

Precise metallic parts of complex 3D geometries are used in superconducting coils of high-field accelerator magnets. It was demonstrated that part prototyping using AM technologies and plastic materials is an effective way to finalize part designs and reduce their cost during production. This approach is now used on the regular base at Fermilab. Various AM technologies to produce parts for accelerator magnet coils using various materials, such as SS 316L, Ti6Al4V, Inconel, etc., are being developed. These parts have already been used successfully in real superconducting accelerator magnets.

The SMCT coil is a new concept which was proposed at Fermilab for high-field and/or large-aperture accelerator magnets based on low-temperature and high-temperature superconductors with the coil ends of challenging complexity. The first set of SMCT coil parts for Nb_3Sn dipole coils [6] have been produced by GE Additive using DMLM technology. Printed parts have been measured using a laser scanning system with acceptable results. The SMCT coil winding will start shortly after parts post-processing. Parts for the Bi2212 insert coil [12] to be produced using AM technology are being designed and optimized using practice plastic parts.

6. References

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