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FABRICATION OF THE HELICAL FIELD COIL COMPONENTS FOR THE ADVANCED TOROIDAL FACILITY*

M. J. Cole and J. C. Whitson
Martin Marietta Energy Systems, Inc.
P.O. Box Y
Oak Ridge, TN 37831

B. J. Banks
CBI Services, Inc.
Birmingham, AL 35550

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Abstract

The fabrication techniques used to manufacture the major components of the helical field (HF) coil segments for the Advanced Toroidal Facility (ATF) are described. The major components of an HF coil segment are 14 water-cooled, copper conductors and a T-shaped stainless steel support member (or "tee"). Twenty-four of these segments were used in the fabrication of two coils for the ATF experiment. The helical shape, accurate position requirements, large size, and potential for high cost required unique approaches to the fabrication of these components. One method of fabrication was to use 44-mm-thick (standard size) plate to form the base and leg of the tee and to join the sections by welding. Because of the tolerance requirements, a thicker plate (70 mm) was used and then contour machined to the final shape. The second approach, conducted in parallel with the first, was to cast the tee as a single piece. The first attempts were to make the casting larger than required, then machine it to final size and shape. The cost of machining either the welded tee or the cast tee was extremely high, so several prototypes were fabricated until a cast tee that required no contour machining was produced. The shape and positional requirements were also the major problems in fabricating the copper conductors, or turns. The approach taken was to make an accurate fixture and position the turns in the fixture, then anneal to remove residual stresses and form the copper turns to the shape of the fixture. The lessons learned in pursuing these fabrication methods are presented.

Introduction

The ATF is a torsatron (stellarator) now under construction at the Oak Ridge National Laboratory. Detailed descriptions of the ATF device have been previously reported at other symposiums and in other publications.[1-3] Figure 1 is a sketch of the ATF device.

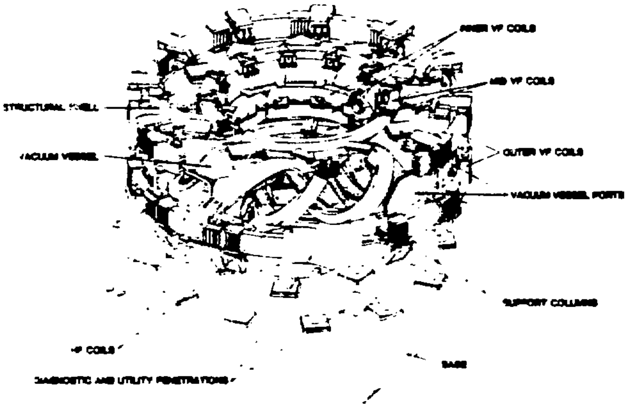

Fig. 1. Advanced Toroidal Facility isometric.

Design and Fabrication Requirements

Three major areas caused difficulty during design and fabrication of the HF coils: the helical shape, the high degree of accuracy required during operation, and the goal of fabricating the HF coils in parallel with the vacuum vessel to permit installation of a portion of the coils prior to delivery of the vessel.

Shape

A wide range of stellarator configurations was studied before the ATF HF coil geometry was selected.[3] The resulting geometry was an $l = 2$, $m = 12$ torsatron with a modest aspect ratio of 4.6. The final shape, as shown in Fig. 1, was a helical coil with a high degree of twist. The problems associated with fabricating the coils were (1) how to build such a large, complex shape at a price the project could afford and (2) how to measure and inspect this shape to ensure that it met the high degree of accuracy required during assembly.

Required Accuracy

To prevent the formation of magnetic islands and the distortion of flux surfaces, the centroid of the HF coil current path had to be maintained within 1 mm of the theoretical current path. Once again the problem of inspecting and measuring the location of the helical shape was very critical to the fabrication of the coils.

Parallel Fabrication

The decision to fabricate the HF coils in parallel with the vacuum vessel meant that the HF coil would have to be split or divided to permit assembly of the machine. As a result, each HF coil was divided into 12 segments that join with a demountable joint at the horizontal centerline of the device, as shown in Fig. 2.

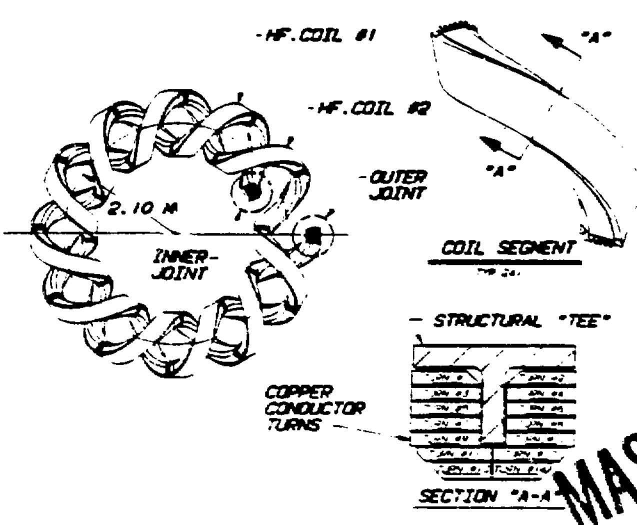

Fig. 2. The HF coil concept.

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Measurement and Inspection of HF Coils

The problem of positioning a complex object in a given region of space can be described in the following manner. Figure 3 gives definitions for the symbols used in this section. Suppose that an object A is described in coordinate system X by a set P of measured coordinates $(P_1(x,y,z), P_2, \ldots, P_n)$. The object is to be positioned in some optimal way into the volume given by $A' \cdot A'$ is described in coordinate system X' by a set of points $P', \ldots, P'_n$. The selection of features that describe A and A' should be chosen such that they are close together after the object is positioned into the volume A'. The connection between the coordinate systems X and X' is initially unknown and is to be determined such that we have an optimal fit. The functional equations describing the transformation of coordinates in X to X' are written as

$$X' = BX + T \ ,$$

where X and X' are matrices whose elements are the values of the coordinates in their respective coordinate systems. T is the translation matrix connecting the two origins O and O'. B is a 3-by-3 orthogonal transformation matrix. The representation chosen for B is purely one of convenience. We chose the Eulerian angles ϕ, θ, and ψ. ϕ is the initial rotation above the z-axis, θ is the second rotation about the new x-axis, and ψ is the third rotation about the new z-axis. This is the standard order given in many textbooks.[4] The problem of determining a best position for A is one of finding the values of ϕ, θ, ψ, T_x, T_y, and T_z that allow one to calculate the coordinates of the features of A in the X' system and have features close to their intended positions. The distance between P_n and P'_n is given by

$$\vec{D} = \vec{r}_n - \vec{r}'_n \ ,$$

$$D^2 = X^T X = X^T(Bx + T) = f(\phi, \theta, \psi, T_x, T_y, T_z) \ ,$$

where X^T is the transpose of X. One can construct the term $W = \frac{1}{2} k_n D^2$, where $k/2$ is an arbitrary constant. W_n is just the equivalent of the energy stored in a linear spring connecting points P_n and P'_n. Our experience indicates that it is convenient to decompose the vector $\vec{D}$ into components whose directions can be chosen to suit a given problem. The W is then written as

$$W_n = 0.5 \sum_i k_i D_i \hat{e}_i \qquad i = 1, 2, 3 \ .$$

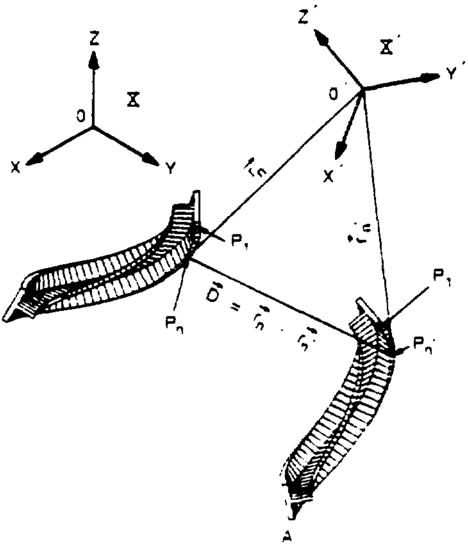

Fig. 3. Definitions of symbols.

Thus, the notion is to construct a system where we connect springs between a measured point and its ideal position in space. We break the spring into three equivalent springs, each with an independent spring constant and direction. Another degree of freedom can also be implemented. If one measures the points P_1 to P_n such that we can use a spline to interpolate between points, we can allow the point P to slip along a smooth curve through the points P_1 to P_n. We construct the functional $W = \sum_N W_N$, which represents the total energy in the system, and minimize it in an unconstrained manner. The result is a rotation and translation that minimize the energy in our spring system. The minimization process is a standard algorithm in nonlinear optimization.[5] By using a technique like the one above, we can define in a statistical sense a position for an object in space. The error analysis of the position is a natural part of the solution. The above is an application of the idea of least squares to fitting a three-dimensional object to its design position. Armed with the knowledge of the position of the coil, we mounted about 10 small tooling balls on the outer surfaces of the tee, located their centers with the coordinate measuring machine (CMM), and translated their locations to the ATF coordinate system. These balls then served as easily measured reference locations for the part. We call this the concept of a "floating datum."

Fabrication of ATF Components by CBI

Fabrication of the components of the ATF coil involved two distinct structure types: (1) a structural tee section of either welded or cast 304L stainless steel and (2) a set of B152 copper conductors formed to match the helical shape of the structural tee.

Structural Tee Fabrication

In preparation for forming the base and leg of the welded tee sections, a program was begun to develop a forming die to be used in a 13.3-MN-capacity hydraulic press. Because of the complex shape of the two components, a small prototype die was first made that was capable of forming scale-model components from aluminum and 12.7-mm-thick stainless steel. With this prototype, acceptable helical components were formed. The prototype was then scaled up to a die capable of forming the 70-mm-thick components on the 13.3-MN press. Experienced operators used this die to form the base and leg of the 70-mm tee to meet the required contour tolerances. To limit distortion during welding and to maintain the formed shape, the two components were then fit into a massive cradle consisting of a 152.4-mm-thick base plate and 38.1-mm-thick ribs spaced about 101.6 mm apart. The base was secured to this cradle with welded lugs, and it remained in this position until all welding was complete and a dimensional stability post-weld heat treatment cycle was complete. The welded tee section remained stable after removal, and no distortion was noted. The welded 70-mm tee was then inspected by using a CMM to determine whether a finished 44-mm-thick tee section could be machined from this oversize section.

Welded Tee Machining

This section was machined on a horizontal boring mill (HBM) by using multipass techniques with a ball-nosed end mill. Programming for the helical shape required several weeks of computer programming and five different setups to be able to machine the part. Although it was possible to machine a part that fully met the tolerance requirements of the project, the cost and schedule were prohibitive. Therefore, an alternate approach of casting a tee section to proper size that required only a minimum of machining for contour was judged to be the most feasible.

Cast Tee Machining

Cast tee sections were received by CBI Services, Inc., after they had been inspected on a Cordax CMM and after tooling balls were fixed to the part and located by the CMM. The tees were placed on a machining fixture and positioned to within 0.127 mm of theoretical location using the CMM and the tooling balls. The fixture with the tee in place was then moved to an HBM and placed on a machined base. Again, alignment of the part was checked by using the tooling balls. After several setups, the ends of the part and the bolt holes at Datum 91 (center) were completely machined.

Once the HBM work was completed, the part was removed from the HBM, moved to a tilting, rotating table under a drill press, and positioned in a holding fixture with the leg down and the back side of the base presented to the drill press. A special drill fixture developed by CBI was then attached to the base of the tee using the two bored holes at Datum 91 and the machined end features of the tee for reference. All remaining features were then machined using the drill fixture and conventional tooling. All features were held within the specified location tolerance using this arrangement with all dimensions verified by CMM inspection.

Fabrication and Assembly of Copper Conductors

Material for the conductors consisted of B152 copper plate material machined on both sides to maintain a uniform thickness of 31.75 and 34.925 mm. The rough shapes for each part were first burned by using an underwater plasma cutting process mounted on a computer-driven burner; programming of the shapes was a very difficult task because of the lack of symmetry of the parts. After burning, the parts were inspected using a computer-generated overlay template. Extra stock (12.7 mm) was left on all cut edges to be machined later.

Each copper part was then mounted on a CNC horizontal boring mill by using special fixturing developed specifically for this project. The final contour, cooling tube groove, end tab contour, lifting eye holes, and throughbolt holes with counterbore were all machined at this point. Throughbolt holes were drilled to 19.05 mm diam and later enlarged to 25.4 mm diam during the final forming procedure and 35.7 mm diam after all forming was complete.

At each step in the manufacturing process, inspections were made to ensure that all features were within tolerance at that particular stage of manufacture.

Following inspection of the machine parts, each was set up in a clean area to install the 12.7-mm-diam copper cooling tube. Copper turns and cooling tubes were cleaned with an acid solution and 1,1,1-trichloroethane to remove any oxides or other residue that might interfere with the brazing process. The copper cooling tubes were then hand-worked using tube benders and fit into the cooling groove in each turn. In those turns intended to be toward the center of the machine, a 9.525-mm-diam "squirt" tube was also fitted into the end tabs to provide cooling for that area.

After cleaning and fitting of the tube, silver-copper eutectic brazing alloy in wire form was placed on the intersection area between the tube and turn. These assemblies were then placed in a closed steel container to be brazed in an electric furnace at 816°C with an argon gas purge in the container and an oxygen content of 0.4% or less. The brazing wire became fluid at this temperature and flowed around the tube to form a 100% bond. Argon flow was maintained until the assemblies cooled to 150°C.

The next step in the fabrication was to "slip"-roll the turn into a spiral shape, approximately meeting the final shape requirements by using a plate bending roll. This allowed the turns to be fit into the final forming fixtures. Each cooling tube was leak tested at this point to ensure that the tube had not been damaged during the rolling process.

Fabrication of Forming Fixture

Three forming fixtures were available for this project. Each was machined by Martin Marietta Energy Systems, Inc., to match the required contours of the copper turns and to interface with the end tab holding and machining fixtures. The end tab fixtures were designed to hold the end of each turn in place during the forming of the turns and later as a drill guide to line-drill and ream the holes in each stack of turns to make later assembly of the stack sets possible. The plates in this fixture were machined and ground to size to ensure that the exact spacing between the end tabs in each stack was maintained.

Machining such a complicated part, even on a numerically controlled five-axis milling machine, requires several setups to reach all surfaces. The usual technique for doing this is to move the part into the "correct" position for each setup and then do the machining. Because of the large size of these parts, their complicated shape, and the high level of accuracy required, it was very time consuming and nearly impossible to position the parts correctly on the machine bed. Once again, the floating datum technique proved invaluable. The part was adjusted to approximately the correct position (since it barely fit on the machine). Then, the tooling balls were measured with the milling machine to specify the transformation between the ATF coordinate system and the milling machine coordinates. By using a VAX computer it took only about 20 min to make a new machine tape with no readjustment of the part location. In contrast, attempts at manual setups took up to a day and did not yield accurate results. In addition, by carefully choosing the machining geometry, the two ends of the fixture could be machined simultaneously so that the locations of the two ends of the coil were held to within 0.051 mm of true position.

Final Forming (Stacking) of Turns

Turns were placed in order on the tee-shaped forming fixture with Nos. 1 and 2 against the flange of the tee and Nos. 13 and 14 in place above the web of the tee and away from the flange. As each turn was put in place, it was pushed to fit the fixture by using hydraulic jacks, clamps, and hammers. Fitting was complete when the turn was tight against the fixture and/or the previous turn. Gap was determined by using feeler gauges; the gap between turns and the height of the stack were inspected and recorded at each level. If adjustments in the height of the stack were necessary, the copper shim thickness between the turns was adjusted to increase or decrease the height. As the fitting process at each level was completed, 1-in.-diam pins were pushed into the stack through holes drilled into the turns. These holes were drilled by using special fixturing developed by CBI for this particular job. Because of the shape of the parts, these pins locked the stack of turns into position and prevented any movement as subsequent operations were performed. With the turn completely formed and in place, the end tab fixtures were against the end tab on each turn; no gap was allowed between the fixture and the copper turn. Each of the 14 turns was placed on the fixture in the above sequence.

The completed stack of turns, pinned to the fixture, was then placed in a closed steel box, which allowed an argon purge during an anneal cycle. The annealing heat treat cycle stabilized the copper so that no movement was apparent when the stack was later released from the forming fixture.

The annealed stack of turns was moved to a machining station where the end tab holes were drilled and reamed to 19.05 mm diam with a 0.127-mm tolerance. This operation was performed by using portable magnetic-based drills and by using the forming fixture's hardened drill bushings to maintain positional tolerances. A 19.05-mm pin was placed in each hole as it was completed to ensure that all holes were in the correct relative position.

Following the end tab drilling, the 25.4-mm-diam pins were removed from the stack, and by using portable equipment and a specially designed drill fixture, the 25.4-mm-diam holes were drilled and reamed to 35.712 mm diam. As each hole was completed, a tight-fitting pin was inserted into the hole to ensure that the correct relative position of each hole was maintained. The pins in the end tabs and the pins in the throughbolt holes were removed after the holes were drilled. Upon removal of the pins, a "spring-back" movement of 1.588 mm was noted on each end of the innermost turns.

To ensure the integrity of the cooling tubes after all work was complete, the tubes were subjected to pressure testing and a halide leak rate test, after which the turns were final cleaned, stacked in sets, and boxed for shipment.

Notable Problems in Manufacture

The change from plain end turns in the prototype stage to the bolted end tab connection in the final design created some difficulty in fabrication. The plain end allowed the turns to be trimmed to length after all work was complete, but the final end tab design forced an exact length determination before any forming was done. On the first few turns, the parts appeared to be longer than allowed, as evidenced by interference between the main body of the turn and the end tab fixture. Careful study of the problem showed that the geometry of the part created the interference and that the problem could be resolved by trimming back the body of the turn about 3.175 mm at the end tab intersection and cutting the turn to final length after all work was complete. Special fixturing was developed to allow this work to be done with a portable, air-powered router with carbide tooling. With this change, all parts were produced to meet the contract requirements and ensure a very good turn-to-turn electrical connection.

Summary

The HF coil set for ATF posed a very difficult and challenging set of fabrication problems. The complex shape required special methods of casting, forming, and fixturing to maintain the 1-mm current center positioning for final assembly. Unique inspection and measurement methods were developed to fabricate forming fixtures and to optimize the fit of each component. These fabrication techniques produced component parts that meet specifications within the original estimated cost and schedule.

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