NCSX Component Fabrication Challenges

L. Dudek, J. Chrzanowski, M. Viola, P. Heitzenroeder, T. Meighan, S. Raftopoulos
Princeton Plasma Physics Laboratory, PO Box 451, MS-40, Princeton, NJ 08543

Abstract— **The National Compact Stellarator Experiment (NCSX) is being constructed at the Princeton Plasma Physics Laboratory (PPPL) in partnership with the Oak Ridge National Laboratory (ORNL). The stellarator core is designed to produce a compact 3-D plasma that combines stellarator and tokamak physics advantages. The complex geometry and tight fabrication tolerances of NCSX create some unique engineering and assembly challenges. This paper will describe a few of the challenges of the machine's Modular Coils and vacuum vessel field period assembly and how they are being solved. Coil assembly began in November 2005 and to date 3 Modular Coils have been completed. One vacuum vessel 120° section has been delivered and field period assembly work began in May 2006. Machine sector sub-assembly, machine assembly, and testing will follow, leading to First Plasma in 2011.**

Keywords-NCSX; Fabrication; Coils; Chill Plates

I. Introduction

The National Compact Stellerator Experiment is a new device being built to study physics of compact stellerators at PPPL in partnership with Oak Ridge National Laboratory. The main assembly of the device consists of eighteen Modular Coils, TF coils, and three vacuum vessel segments. These major components are now being built at PPPL in an assembly hall. The final assembly of these components presents some unique challenges for the engineer. This paper describes some of the challenges and how they are being solved.

II. Material Challenges

A. *Material Permeability*

The permeability requirements for the NCSX are extremely challenging, all materials inside the cryostat must have a mu < 1.02 as measured with a Severn gage. This reduces the number of suitable material choices available and in many cases increases the material costs due to the selection of high nickel metals over less expensive austhenitic stainless steel. In an attempt to find more alternatives, tests were performed on 316SS to reduce the permeability to acceptable levels. One of the port covers for the NCSX Vacuum Vessel was measured to have a mu of 1.7 on both side and the edges. A furnace heat treatment run was performed on the part to anneal the part and reduce permeability. The furnace used was a high vacuum / 2 bar gas quench furnace capable of 1300 C operations and a gas quench from this temperature to ambient in about 15 to 30 minutes depending on furnace load. The furnace schedule used followed the recommended procedure in ASM vol.3 Properties and Selection Stainless Steels, Tool Steels and Special-Purpose Metals [1]. This is a general description; some modification of this procedure was required due to the equipment used in the heat treating. The furnace run schedule ramped, under vacuum, at 15 C per min to 1100 C, soaked, under vacuum, at 1100 C for 180 mins, argon gas quench set to a pressure of 12 psig, which cooled the flange to below 425 C in approx 5-10 mins. It should be noted that this schedule is used as a general austhenitic stainless steel annealing schedule, the ramp rates, soak time and gas quench are varied depending on the desired results required at the time. The 1100 C temperature setting is never varied. Part size and mass dictate the choice of the other parameters. After the heat treatment cycle the permeability dropped from 1.7 to <1.1 as measured with the Severn Gage.

This method of heat treating allowed the use of 300 series stainless steels instead of more costly Inconel resulting in a net cost savings to the project.

B. *Chill Plates*

Each Modular Coil employs copper plates encircling the coil winding to carry thermal energy away in liquid nitrogen filled cooling tubes [2]. There are approximately 800 uniquely shaped chill plates on each Modular Coil. While the dimensional requirements for these parts are not critical each plate must be clean and burr free to ensure that sharp edges or dirt can't damage the electrical insulation. The original plan to fabricate the parts was to use a waterjet machining center to cut the parts in the flat from DXF files generated in ProEngineer. Once the parts were cut in the flat the ends are formed to create interlocking corners in order to transmit the heat away from the coil.

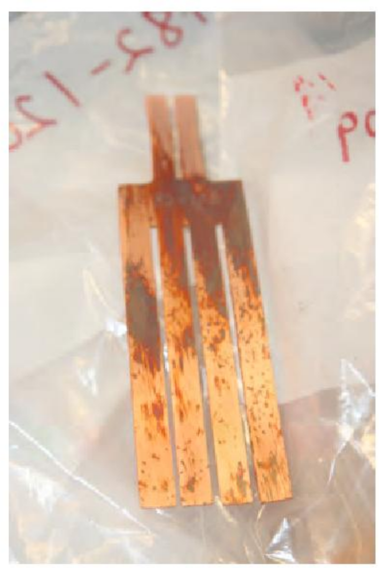

Figure 1. Wire EDM Chill Plate before cleaning

This work is supported by DOE contract DE-AC02-76CH03073

The first batch of chill plates cut using the waterjet method had acceptable tolerances (+/- 0.010") however the process left a sharp burr on the backside of each piece, which were removed manually to avoid damage to the delicate parts. The budget allocated to the chill plates was approximately $3 each but with cleaning and deburring the cost grew to almost $25/ piece.

A new manufacturing method was sought for subsequent batches and laser cutting was chosen for the second batch. Lasercutting copper requires some precautions to be taken before machining to prevent damage to the laser optics from reflections of IR energy off the highly infrared reflective copper. The method chosen required painting the copper sheets with a water-soluble paint to make them non-reflective before lasercutting. Once cut, the parts still needed deburring but for this iteration an automated process was used which improved the cost, but still required some final cleanup of the edges due to a carbon residue left on the edges from the laser cut. This reduced the total cost of the chill plates by approximately 50% which was still significantly higher than budgeted.

The last batch of chill plates was fabricated using a multilayer wire Electric Discharge Machining (EDM) technique. The raw material was stacked six layers deep while the parts were cut in deionized water. This method yielded the best results with the minimum amount of post work. The wire EDM method yielded burr free parts, only a mild cleaning process to remove some staining left from the deionized water. Final piece cost using this method was approximately $6 per piece.

C. *Inflatable Shims*

There are 18 Modular Coils wound on 6,000 lb. castings. They are connected to each other via heavy cast flanges. Several of the coils nest into the adjacent coil creating regions of overlap and unsupported "wings". The regions require support to have acceptably low levels of deflections during operations. The method investigated for this support was an inflatable shim between the two coils. The shims are required to resist a compressive load of 17 KSI at liquid nitrogen temperature (77K) for 30,000 cycles. The design selected for testing consisted of a FEP polymer envelope (0.005" thick) filled with dry chopped fiberglass vacuum/pressure impregnated (VPI) with a CTD 540 epoxy formulation. FEP was chosen over polyethylene for its higher strength and higher working temperature.

TABLE I. REQUIREMENTS FOR THE BLADDER SHIM ENVELOPE

Item	Requirement
Installation Temperature	300F (145C)
Operating Temperature Range	-320F to 212F (-196c to 100C)
Max. Compressive Load	17.4 KSI (180 MPa)

Initial tests of the shims were performed using standard rectangular shaped FEP bladders. The tests were performed to verify the epoxy injection method using a pneumatically driven injection gun and the ability to have acceptable quantities of fiberglass in the envelope. The first tests used 100 - 250 g of chopped fiberglass in the bag which was inserted into the bag by cutting a corner, stuffing the bag and resealing the bladder using a thermal sealing tool. These tests demonstrated that the bladder can be easily stuffed with fiberglass, filled with epoxy in approximately 20 minutes. The cure time to gel for the shim was approximately 60 minutes.

Figure 2. Inflatable shim partially filled with epoxy during injection test

The samples produced from these tests were tested at 77K for their mechanical properties and were found to have compressive strength above the required 17 KSI (Fig. 3).

Additional testing is planned to fill a prototype shim bladder while in place between two Modular Coils to demonstrate the injection method.

TABLE II. SHIM EPOXY REQUIREMENTS

Trial	Epoxy	Thickness	Fiber Content	Fill Rate
1	CTD 540	1/4"	100 g	> 60 min.
2	CTD 540	1/4	150	~ 20
3	CTD 540	1/2	250	~ 20
4	StyCast 23LV	1/2	250	>> 60

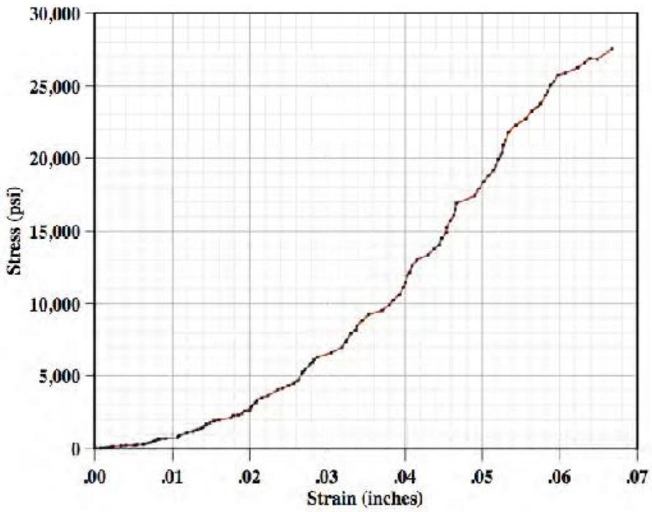

Figure 3. Stress – Strain Data for Fiber Filled Shim

III. Fabrication and Assembly Challenges

The next major assembly challenge on NCSX is the assembly of the Modular Coils. The coils are assembled in sets of three (one A, one B and one C type coil) prior to their installation onto the vacuum vessel. The coil joints must resist the forces of operation of approximately 4000 lbs per linear inch of joint. In order to ensure a reliable joint the design is using both tight fitting bushings around the fastener and high friction coatings on the shims.

A. Coil to Coil Assembly and Alignment

The Modular Coils on NCSX consist of 6 each of 3 types, A, B and C. The coils are wound onto a Stellaloy metal casting which has properties similar to 316ss with low permeability and good cryogenic properties. Each coil casting has a flange on each end to bolt to the adjacent coil. The positions of the coils are controlled through the use of nominal 1/2" thick Stainless Steel shims alumina coated for friction and electrical isolation purposes. The thickness of these shims is varied slightly to maintain the proper alignment of the coils to meet the design tolerances and to maintain stellerator symmetry.

1) Coil to Coil Gap Adjustments

To simplify the gap adjustment, the shims are made in a standard shape, one for each bolt, to allow discrete thickness sizing. An inventory of shims of various thicknesses will be used to eliminate field machining or grinding of shims and minimize cost and schedule. There was a concern the steps in the shim thicknesses may create areas, which are under compressed. Tests were undertaken to determine how large of a thickness error could be tolerated between adjacent shims and still maintain good contact pressure (Fig. 3). A pressure sensitive film made by FUJI Corporation was used to measure the contact pressure. The film changes from white to red in proportion to the pressure being applied. The film has a range of 1,400 - 7,100 PSI (100 - 500 kg/cm_2). The fasteners used in the joint were torqued to 50% of the full tension of 58,000 lbs. to avoid any yielding of the Modular Coil casting threads. The thickness of one of the shims was varied in 0.001” increments to characterize the effect on pressure.

Figure 4. Two Modular Coils being assembled to test shim pressures

The results of these tests can be seen in Fig. 5. The conclusion from these tests was that thickness must be controlled to within 0.001- 0.002” in order to ensure good pressure on the shims over 30% of the surface area.

2) X-Y Positioning of the Coils

A second series of tests were conducted to demonstrate the ability to adjust the x-y position of the coils to within the tolerance budget of 0.010”. A pair of coils was mated on a wedge shaped fixture and outfitted with a pair of dial indicators on each corner. A laser tracker was used to measure the position of the lower coil and then the upper coil [3]. A set of coordinates was established to move the upper coil to and the dial indicators were used to position the coil. A computer spreadsheet was used as an aid to input the desired coordinates and get the required dial indicator readings to achieve the result. It was found that positioning of the coils could be achieved to within 0.001-2”.

Further testing is now being planned to demonstrate the effects of the friction coatings on the alignment technique and then alignment techniques for multiple coils.

B. Inboard Coil Flange Welding

The plan for the inboard leg of the Modular Coils is to weld the coil castings where they meet the ½" thick spacer shim. This eliminates a small displacement between coils that was identified in the structural FEA analysis. A rudimentary first test of this plan was conducted using 1-1/2" thick stainless plates as shown in Fig. 6. The purpose of this first test was to determine if the expected weld distortion would be excessive, which was not the case. Further numerical analysis of the weld distortion is planned to identify slight design changes that can still be made to reduce the distortion to the minimum. The goal for this work is to weld the inner leg distorting the Modular Coil track < 0.010".

Figure 5. FUJI Film Test results showing effect of varying shim thickness

Figure 6. First Test of Modular Coil Flange surrogate weld

SUMMARY

The fabrication and assembly of the NCSX device presents challenges in every aspect of design, fabrication, and assembly. These challenges are being solved by analysis, testing, and assembly trials. The remaining challenges, the inflatable shim bag and the Modular Coil joint still need further refinement. Individual components for these designs are now being tested are are expected to be completed in the near future.

REFERENCES

[1] ASM vol.3 Properties and Selection Stainless Steels, Tool Steels and Special-Purpose Metals, pages 46, 47 and 48 sections under Heat Treating, Annealing and Stress Relieving.

[2] J.H. Chrzanowski, P.J. Heitzenroeder, T. Meighan, P.J. Fogarty, etc. "Manufacturing and Development of the NCSX Modular Coil Windings" presented at 21st. SOFE Conference in Knoxville, Tenn., October 2005.

[3] S. Raftopoulos, A.W. Brooks, R.A. Ellis, M.J. Duco and T. G. Brown, "Metrology for the NCSX Project", presented at 22nd. SOFE Conference in Albuquerque, NM., June 2007

[4] W. Reiersen, B. Nelson, P.J. Heitzenroeder, etc., "Progress in NCSX Construction", presented at 22nd. SOFE Conference in Albuquerque, NM., June 2007