LAMBERTSON UPGRADE PROGRAM

Katharine J. Weber
Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Ill. 60510 USA

Abstract
An investigation of a vacuum failure of a Lambertson magnet has resulted in a program to re-evaluate the materials and the method of construction of these magnets. Three additional failures have occurred since the first event. Lambertson magnets are now being built and repaired based on knowledge gained through research aimed at eliminating this type of failure in the future.

I. INTRODUCTION

A Lambertson consists of an inner core, surrounded by a vacuum skin, an outer core and coils. The inner core, consisting of a stack of laminations, tightly enclosed by a vacuum skin, sits inside an outer core of stacked laminations. There is a cover over the entire top of the magnet.

Over a two year period, four Lambertsons were found to have leaks in the vacuum skin. In addition, three additional Lambertsons are suspected to have leaks. As a result of this, an investigation was conducted and a repair and replacement program was instituted. The conclusion of the investigation was that the stainless steel vacuum skins were failing due to intergranular corrosion.

Intergranular corrosion may occur when the stainless steel undergoes a thermal cycle, called sensitization. When the stainless has been sensitized there is precipitation of a carbide, nitride or other inter metallic phase. This causes the dissolution of the grain boundaries, or closely adjacent regions. If the precipitation is relatively continuous, the depletion renders the stainless steel susceptible to intergranular corrosion.[2]

In austenitic stainless steels, such as the type used for vacuum skins, the cause of intergranular attack is the precipitation of chromium rich carbides at grain boundaries. This leaves the stainless steel vulnerable to rapid attack by all forms of corrosion. Certain alloys that are highly resistant to general and localized attack, such as the 300- and 400-series of stainless steels can be affected by intergranular corrosion. Sensitization of austenitic stainless steel can occur when heated in the range of 425 to 870C, with the maximum effect occurring near 675C. Sensitization of stainless often occurs in non-stabilized grades during the welding process.

Stainless steels that have normal carbon content but do not contain any carbide-stabilizing elements are most susceptible to sensitization and intergranular corrosion. Type 304 stainless can be sensitized in about 1 minute at 677C. The most common stabilized grades of stainless are 321, 347, 316Ti, 309Cb and 310Cb. These stabilized grades use titanium, or niobium with tantalum in concentrations of about ten times the carbon content. When these grades are subjected to thermal cycles in the sensitization range, the carbon-stabilizing element forms a precipitate with carbon leaving the chromium in solution. The stabilized grade remains resistant to corrosion.

Stabilized grades of stainless are given a treatment at the mill to ensure that the material is properly stabilized. This treatment consists of heating the material to its solution temperature to dissolve any carbide that may be present. A subsequent heat treatment in the sensitization range precipitates carbides with the stabilizing element, such as titanium, as opposed to chromium.

Although stainless steels are susceptible to several forms of localized corrosive attack, with appropriate grade selection, stainless steel will perform for very long times with minimal corrosion. An inadequate grade of stainless can corrode and perforate more rapidly than plain carbon steel will fail by uniform corrosion. The corrosion performance of stainless steels can be strongly affected by practices of design, fabrication, surface conditioning and maintenance. Corrosion failures in stainless steels can often be prevented by suitable changes in design or process parameters and by use of the proper fabrication technique or treatment.

The vacuum skin on the failed Lambertsons was analyzed and determined to be type 304 stainless steel. This grade could not provide the corrosion resistance required for the application. In addition, the material was sensitized during the fabrication process as well as exposed to corrosives.

The repair and rebuild program effected not only the upgrade of stainless steel used, but re-evaluated all the fabrication processes as well. This program is detailed in the following paragraphs.

II. MATERIAL SELECTION & PREPARATION

A. Vacuum Skin Material Selection

Data from log books indicate it was a common occurrence to bake the inner core in the sensitization region. Actual samples removed from the failed skins were examined. They were all found to be sensitized. In addition, samples of the stainless grades used for vacuum jackets were subjected to the conditions outlined in the log book. Under microscopic examination all the samples proved to be sensitized. Type 321 stainless is a grade that has been stabilized with titanium to prevent chromium carbide precipitation. Since this grade is the most commercially available of the stabilized grades, 321 was chosen for the new vacuum skins. Samples of the 321 stainless were subjected to the bake conditions in the log book, and none were sensitized. An additional test was done on the purchased material to verify that the 321 stainless had a sufficient concentration of the stabilizing element, titanium, and that the material had indeed received a stabilizing treatment at the mill. [2]

B. Surface Finish

The optimum surface finish for a satisfactory service life should be one that is smooth and free from surface imperfections, scale and other foreign material. Rough surfaces are more likely to catch dust, salts and moisture,

0-7803-1203-1/93$03.00 © 1993 IEEE

which can contribute to corrosive attack. An 2BA surface finish is an example of a smooth surface finish.

Type 321 stainless can only be obtained with a 2D finish. In addition, because of the titanium content, this material is difficult to mechanically polish. Electropolishing proved to be the best choice for this application.

Electropolishing can reduce the micro-inch value of a surface by 33% to 66%. Electropolishing removes the "skin" and along with it, all sources of impurities that could become a point for corrosion. This process provides a superior resistance to corrosion as compared to passivation.

In addition, electropolishing is beneficial in vacuum applications by eliminating gases, vapors, and volatiles absorbed on surfaces, which would later be released during pump-down for high vacuum. [2]

C. Vacuum Skin Cleaning

Samples taken from the failed vacuum skins revealed significant amounts of chlorine present in the depleted grain boundary areas. Steps were outlined for the new type 321 stainless steel skins to keep them from having contact with any corrosives.[2]

In order to minimize the possibility of corrosion, chemicals should not be used on or near stainless steel whenever possible. Any chemical that does come into contact with the stainless steel should immediately be washed off, followed by a liberal rinsing with alcohol then distilled water. No chemical should be allowed to remain or evaporate on the stainless steel.

The most common corrosive is chlorine, such as in chlorinated solvents, tapping compounds, cutting fluids and fluxes. Chemicals containing chlorine should never be used. Many manufacturers are now distributing these types of products in a non-chlorinated form.[4] Sensitized stainless steel in combination with chlorine is especially likely to exhibit extensive corrosion. Any chlorine residue can initiate corrosion in unsensitized stainless steel, particularly if the steel is subsequently heated. Hydrochloric acid formed from residual amount of a common solvent, trichloroethylene, has caused severe attack in stainless steels.

Oil and grease can be removed by using a detergent and water solution. Weak concentrations of cleaners that contain phosphoric acid have also proved to be successful in removing dirt and grease.[4] All cleaning solutions should be rinsed thoroughly after cleaning. An alcohol rinse will dissolve any cleaner residue left. Follow this with a liberal distilled water rinse, then dry with warm air, dry nitrogen or clean wipes.

D. Storage

Parts that will be stored for any period of time should be wrapped in brown Kraft paper and placed in box. The box should be kept in an out of the way area, protected from weather and any accidental spills.

E. Lamination Material Selection

Lamination material from the original Lambertsons still remained in stock. Inspection and testing of this material revealed the coating on the material to be protective in nature but not offering any resistive properties. Discussions with physicists and manufacturers culminated in a specification outlining all required properties for the lamination steel.[12] Criterion was set for acceptance testing of the material. These tests were done by Fermilab or an independent vendor.

It was mandatory that vendors not use any chlorinated solvents on lamination material, since the lamination stack is encased by the 321 stainless skin.

F. Lamination Cleaning

Laminations were washed by Fermilab before stacking. They were cleaned in an automated cleaner with a solution of detergent and water. Laminations were rinsed and hot air dried. After washing, laminations were vacuum baked to improve permeability, reduce core loss, reduce absorbed gases and as a final cleaning.[3]

III. ASSEMBLY MODIFICATIONS

A. Stacking

Failed inner core vacuum skins can be replaced by removing the old skin and replacing it with a new skin. Because of the difficulty involved in the reskinning as well as the alarming frequency with the failures were occurring a decision was made to make more spare cores. In the case of a failure the entire inner core could be replaced with a new inner core. The failed inner core could then be allowed to cool to an acceptable radiation level for repair. The reskinning would take place at a more relaxed pace.

Previously built Lambertsons have a press fit between the cores, due to the curvature of the inner stack. Examination of the cores proved this to be true, as indicated by hammer marks as well as laminations out of alignment with the stack.

The failed inner core had relatively deep scratches on the exterior of the vacuum skin, apparently from the process of assembling the inner core into the outer core. Scratches like these can contribute to the failures, by becoming a corrosion site.

Tie bars are welded along the stack of laminations to hold them in alignment. The laminations generally have four tie bar slots, two along the top and two along the bottom. The laminations were previously stacked with two of these slots on top and two on the bottom. This required that the two top tie bars were welded, the stack turned over, and the remaining two tie bars welded. This manipulation of the lamination stack (approx. 20ft long) with little or no support on the three remaining sides caused laminations to move out of alignment. The deformation was permanent and led to the assembly problems, and corrosion sites.

Unfortunately we were not able to change the lamination design. If we had been able to do so, careful reevaluation of the lamination shape could have reduced some stacking problems.

The new replacement inner cores were stacked at 90^0 from the original stacking position. This left all four tie bar slots exposed. All tie bars are welded before the lamination stack is moved. In addition all welding is alternated to eliminate any heat concentration in one area, which can lead to stack deformation as well. After stacking the core is straight to approximately .002".[5],[6],[9],[10],[11] After welding, the resulting inner core stack is straight to less than 1/4" from end plate to end plate, approximately 20ft.

In the same manner, the outer core stacking procedure was changed. Outer cores have eight tie bars and three tie plates. The new procedure calls for all tie bars and plates with the exception of the two smallest tie bars to be welded before moving the stack. Welding is done in the same fashion as on the inner core. Outer cores are then surveyed. If the alignment along the inside edge varies by more than .007" over the length of the core, shrink welds are made on the tie plates to bring the core back into alignment.[5]

B. Skinning

The focus in skinning the inner core was to move the core and handle the materials as infrequently as possible. Every time an inner core is moved during skinning, it is supported on a minimum of two sides. The 'top' skin is placed on a skinning table, then the inner core is placed on this skin. The remaining pieces to form the vacuum jacket are then welded around the inner core. The top skin is tack welded in place before the skinned inner core is turned over and the final welds made.[5]

C. Baking

After the inner core has been skinned and leak checked, it undergoes a vacuum bake. The core is baked for 14 days. Special controllers on the heat tapes make sure that the temperature never exceeds 400C. After the bake is completed another leak check is done. Ion pumps are then turned on and left to run until the vacuum reaches 1×10^{-9} Torr. The inner core is then ready for assembly or storage.[5],[8]

D. Assembly

In preparation for assembly, the outer core is placed on the assembly table. The outer core sits on level support bars. The coil is installed in the outer core with spacer insulation in the space between the two cores. The inner core is lifted by four lifting eyes that are welded to the tie bars. The inner core is centered in the beam direction over the outer core and slowly lowered. There is a slight clearance between the two cores if they are both perfectly straight. The inner core is lowered into the outer core as far as it will freely go. If the inner core is not completed seated, bars are then placed across the inner core to help push it into place. There is protective cribbing placed between the bars and the vacuum skin before the bars are bolted to the table. In increments of no more than 1/4" the core is lowered by tightening down the bars, alternating along the length of the core. After the inner core is completely seated, the cover is bolted in place.[5],[6],[7]

E. Disassembly

In the event a Lambertson needs to be disassembled, such as a vacuum failure or for inspection, a special fixture has been built for this purpose. In the past, the inner core was pulled by the lifting eyes on one end then the other until the inner core was jarred loose. The new fixture pulls on all four lifting eyes with a constant force, eliminating any possibility of plastic deformation from the extraction.[1]

F. Surveying The Completed Assembly

After assembly there is a final survey of the magnet, to assure the required straightness through the aperture. The magnet is placed on a granite table and a target is pulled through the magnet. Measurements are plotted to determine where the magnet needs straightening. Shrink welds are made on the outer core to pull the magnet into the desired alignment. After each shrink weld has cooled, the aperture is measured again. The data is replotted and shrink welds made as needed. This procedure continues until the entire magnet is within .007" over its entire length.[5]

IV. CONCLUSION

The Lambertson upgrade program has produced magnets which have an increased life expectancy over the previous magnets. After final survey these new magnets are also much straighter through the aperature, since they were much straighter throughout the assembly process. Careful evaluation of every step, from material selection to final assembly procedure is responsible for the success of this program. All steps outlined above are well documented in procedures, sign off sheet and log books. This program is proof that extra time spent in the design and planning phases of a program can produce superior results.

All documents related to this program can be obtained through the author.

V. ACKNOWLEDGEMENTS

Thanks to M. Kaneshige and R. Kellett for their contributions to the project, and to R. Andrews for his encouragement and support.

VI. REFERENCES

[1] R. Kellett, "Lambetson Inner Core Removal Fixture", Fermi Spec. #1323-ES-296052.

[2] K. Weber, "Corrosion of Stainless Steel Lambertson Skin", Fermi Spec. #1312-ES-296056.

[3] K. Weber, "Cleaning of Lambertson Laminations", Fermi Spec. #1352-ES-296169.

[4] R. Kellett, "Mixing & Using Stainless #330 Aluminum & Stainless Steel Cleaner", Fermi Spec.#1301-ES-296069.

[5] R. Kellett, "A0 D.S.,6" Sym.,F-17,E0 Lambertson Assembly Spec.", Fermi Spec.#1303-ES-296086.

[6] R. Kellett, "Lambertson Inner Core Lifting Instruction", Fermi Spec.#1303-ES-296092.

[7] R. Kellett, "Lambertson Outer Stack Lifting Instruction", Fermi Spec.#1303-ES-296093.

[8] R. Kellett, "Inner Lamination Vacuum Bake", Fermi Spec.#1301-ES-296126

[9] M. Kaneshige, "Lambertson Construction Lifting Fixture, Fermi Spec.#1323-ES-296090.

[10] M. Kaneshige, "Lambertson Inner Core Lifting Apparatus", Fermi Spec.#1323-ES-296097.

[11] M. Kaneshige, "Lambertson Inner Core Rotating Bars", Fermi Spec.#1323-ES-296098.

[12] R. Kellett, "Steel Specification for Lambertson Lamination", Fermi Spec.#1351-ES-296025.