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Cost Reduction for Production of Superconducting Niobium Cavities

Final Report

Frank J. Meyer

Meyer Tool & Mfg., Inc.
Oak Lawn, Illinois 60458

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Abstract

Nine-cell superconducting niobium radio-frequency cavities are used in Linear Colliders. The current manufacturing processes for fabrication of nine-cell niobium cavities requires the deep drawing of eighteen half cells and nineteen electron beam welds. The manufacturing operations required to prepare the half cells for electron beam welding are labor intensive and expensive. Cost reductions in cavity fabrication would provide substantial savings and increase the economic viability of numerous Scientific Research Projects.

This project investigated the feasibility of substantially reducing fabrication costs through the use of a spinning manufacturing process that would ultimately result in the fabrication of three-cell cavities. Fabrication of three-cell cavities would substantially reduce cost by reducing the number of electron beam welds and associated machining weld preparations from nineteen to four.

The major goal of this investigation was to demonstrate that multi-cell cavities could be produced by spinning. Important spinning process parameters were developed. One and two cell cavities were successfully spun. Problems with the developing process were identified and solutions requiring further investigation were developed. Requirements for continuation of efforts to develop a spinning process to consistently achieve uniform thickness in the niobium material and a smooth surface finish without inclusions or tears were determined.

Background

During the past few years, several projects have been constructed or are under construction utilizing Superconducting Radio Frequency Resonant Cavities such as the Continuous Electron Beam Facility at Jefferson National Laboratory, Cornell University, LEP/CERN in Switzerland, TRISTAN at KEK in Japan and HERA/DESY, in Germany. There is a collaborated international effort to build a prototype test bed (TESLA) for a future Superconducting Linear Accelerator. For the test bed alone, there is a requirement of some 70m of superconducting niobium cavities. TESLA will also be a facility for high brightness x-ray Free Electron Lasers (FEL).

At the request of Dr. Helen Edwards of Fermi National Accelerator Laboratory, Frank Meyer attended a workshop on niobium cavity fabrication at DESY in March of 1995. Individuals from the United States and several European countries attended this meeting. The meeting agenda concerned the problems confronting the High-Energy Physics community due to the high costs of fabricating superconducting niobium cavities. The main thrust of the meeting was to find ways to reduce the costs to manufacture the nine-cell cavities that would be required for the TESLA accelerator.

Typically, a nine-cell niobium cavity is fabricated from sheet metal by deep drawing eighteen half cups and requires nineteen electron beam welds to complete a nine-cell cavity. Two cups are electron beam welded together at the iris to produce a dumbbell. Then, each dumbbell is electron beam welded together at the equator to complete a nine-cell cavity.

Electron beam welding requires very close tolerance machining of the cups and time-consuming weld setups in order to perform the welds. This does not include the additional time required to pump down the vacuum chamber, in which the welding must take place, prior to each weld. The weld must also be carefully inspected for full penetration, smooth appearance of the inner bead and absence of any excess material buildup.

At the DESY workshop in 1995, a great deal of time was spent by the attendees relating their experiences and results with different methods of cavity fabrication. The fabrication techniques discussed were:

1. Spinning of niobium, aluminum and copper. Multiple cavities have been formed from aluminum and copper (V. Palmieri, Italy)
2. Hydroforming of copper and niobium. Single-cell cavities have been formed from niobium, multi-cells from copper. (Hauviller, CERN; Jelezov, INR; Stepanov, DESY; Schuller, Butting)
3. Alternative Methods: Explosive forming and hot forming experiments in niobium, with negative results. (H. Padamsee, Cornell)

Spinning from a sheet and hydroforming from a tube emerged from the DESY workshop as the two most promising methods. Laboratories have shown success in making multi-cell

copper or aluminum cavities by both methods. But, a successful multi-cell niobium cavity has not yet been made by either spinning or hydroforming. The other methods (e.g., explosive forming) have yet to reach this stage.

During the performance of this research, we learned that Dr. V. Palmieri of Italy has made a breakthrough, successfully spinning a multi-cell niobium cavity. The methods, techniques, procedures and equipment are of a proprietary nature and documentation, to our knowledge, is not currently available. This breakthrough has proven that spinning is a viable method to produce multi-cell niobium cavities and therefore can significantly reduce the cost to provide multi-cell cavities. Our experiences in Phase I confirms the viability of the spinning technique.

Anticipated Benefits

The technology proven by successfully spinning three-cell cavities will enable the manufacture of multi-cell cavities in a variety of combinations from three to nine cells. The sizes and shapes can be changed to meet radio frequency requirements for large and small-scale research projects.

The prime objective in this research is to reduce the cost to manufacture nine-cell niobium cavities. Successful development of a manufacturing process utilizing spinning technology will radically alter both the process and economies for manufacturing multi-cell niobium cavities. The capability to repeatedly spin single-cell cavities would eliminate the complex machining and preparation for the nine iris electron beam welds as well as the electron beam welds themselves. The capability to repeatedly spin three-cell cavities would further eliminate five cell connection electron beam welds. The successful production of single-cell cavities would eliminate 50% of electron beam welding costs and cavity machining time. The successful production of spun three-cell cavities will eliminate 85% of the electron beam welding costs and 85% of cavity machining time. There will be substantial savings in cost of niobium material, testing, inspection and assembly. The cost reductions would enable laboratories, universities and commercial companies to build small scale superconducting LINACs for research and development projects.

Superconducting cavity-based accelerators can be used for free electron light sources for biomedical and material research. Compact superconducting LINACs could be used for material processing and airport screening systems.

Superconducting cavity-based accelerators will be used as scientific tools for High Energy Physics Research, free electron laser light sources for defense applications, tritium production, transmutation of nuclear waste, conversion of plutonium from disarmament and energy production from thorium.

Technical Approach

Of the alternate techniques for producing nine-cell niobium cavities, spinning is the most technically and economically promising. Spinning utilizes relatively readily available

sheet stock as a raw material source. The capital equipment required for the spinning process is readily available and less costly than competing methods. There exists extensive practical experience in the spinning of a wide variety of materials and configurations, making the processes of developing viable and repeatable manufacturing techniques one of building on an existing established technology rather than breaking entirely new ground.

Since the meeting at DESY, Meyer Tool had contacted twenty spinning companies in the United States to see if there was interest in developing a spinning process for niobium cavities. From this initial contact we selected Superior Spinning & Stamping Company of Ohio as our subcontractor on this research.

For the Phase I research a manually controlled hydraulically powered spinning lathe was utilized. Use of a manually controlled spinning lathe had several limitations but was selected as appropriate for the Phase I research which involved defining initial parameters, limits and methods.

The Phase I work plan included the following stages:

1. Procurement of flat sheets of Grade RRR niobium for spinning of one and two cell cavities.
2. Procure material, design and machine spinning dies for forming single-cell and two-cell niobium cavities. Machine templates for use on the manually controlled hydraulically powered spinning lathe.
3. Spin a single-cell cavity on the manually controlled hydraulically powered spinning lathe. Determine the spindle speed that is most effective for niobium flow without work hardening and maintaining wall thickness uniformity. Determine the proper tool selection for spinning and shaping the niobium on the spinning dies.
4. Remove spinning die from interior of single-cell cavity. Clean and inspect wall thickness, internal and external surface finishes for inclusions, tears and smoothness of the completed single-cell cavity.
5. Spin a second single-cell cavity. Remove spinning die. Clean and inspect wall thickness, internal and external surface finishes, ovality and dimensions.
6. Spin a two-cell cavity.
7. Remove spinning die from interior of two-cell cavity. Clean and inspect wall thickness, internal and external surface finishes, ovality and dimensions.
8. Time permitting spin a second two-cell cavity to verify reproducibility.

Results

The objective of Phase I was to develop a spinning process and a manufacturing plan leading to the ultimate goal of producing three-cell niobium cavities, which would result in lower costs to produce multi-cell cavities. The major goal was to demonstrate that multi-cell cavities can be produced by spinning. A secondary goal was to determine the amount of work hardening (if any) occurred during the spinning operation.

The Phase I work plan was adversely effected by two outside factors, the long lead time of the Grade RRR niobium sheet used to fabricate the cavities and a six week long strike at Superior Spinning & Stamping Company. Despite these factors a substantial and significant part of the plan objectives and goals of Phase I were met.

The Phase I work plan required the staged development of the niobium spinning process and parameters.

1. Niobium sheet stock was procured from Teledyne Wah Chung and donated from Cornell University and Thomas Jefferson Laboratory. Thus the sheet stock used in spinning processes were from different lots allowing assessment of the possible effect of material differences.
2. During the delivery cycle of the niobium sheet, Meyer Tool designed and machined the first article spinning dies for the single-cell cavities. For reasons of schedule and economy in Phase I, non-collapsible aluminum mandrels were used in the production of the first two single-cell cavities. These non-collapsible mandrels were adequate for the initial development of spinning parameters on the single-cell cavities, but would be unsuitable for production type manufacturing. Besides not being re-usable, the non-collapsible mandrels were very difficult to remove from the spun cavities.
3. Initial spinning attempts involved the determination of the most effective spindle speeds and tooling selection to spin a single-cell cavity. On the first spinning attempt we were able to successfully set spinning speeds and parameters to produce a half cell cavity. From the parameters developed in our first attempt, we proceeded to spin a single-cell Grade RRR (250) niobium cavity. With these spinning speeds the niobium material flowed easily with no indications of material work hardening. We were then able to repeat this process and produce a second single-cell cavity.

One of the unforeseen difficulties we encountered involved removal of the non-collapsible aluminum mandrels. After some consultation with Dr. Padamsee, at Cornell we were able to remove the aluminum mandrels from the interior of the single-cell cavities by use of a nitric acid solution. However there still appeared to be some smearing of the aluminum into the interior surface of the niobium. While we were unable to completely remove this surface, it is our understanding that electropolishing solutions do exist that would allow the complete removal of this aluminum residue.

4. During the spinning of the single-cell cavities, non-collapsible aluminum mandrels were designed and machined for the two-cell cavities.

In the initial attempt to spin a two-cell cavity, we learned that the weight of two solid aluminum spinning mandrels was excessive and could not be used on the manually controlled hydraulic powered spinning lathe with any success. We redesigned the spinning mandrel for the two-cell cavities. The new design consisted of aluminum mandrels fabricated in two pieces, hollowed out to .25" wall thickness, welded together and final machined to the outer surface to the cavity shape. With this redesigned mandrel we were able to proceed in our attempt to spin a two-cell cavity.

On our first attempt to spin a two-cell cavity with the new mandrel, we were successful in spinning approximately 70% of the first cell and 25% of the second cell. It was then necessary to go to a narrower spinning tool to spin the niobium to form the iris between the two cells. We achieved about 80% of the depth before a fracture occurred. It was determined that a narrower spinning tool would be required to complete the spinning of the iris to its root diameter. Three more attempts were made to spin two-cell cavities. After each attempt we were able to get a greater percentage of completion and succeeded to within a half inch of the root diameter before failure occurred.

Spinning first cell

Spinning second cell

These attempts showed that to spin two-cell niobium cavities we must start with a minimum material thickness of $5/16$ " in order to maintain the $.128$ " wall thickness of the finished cell. Our single-cell and two-cell cavities were spun from two sheets of reactor grade purchased from Teledyne Wah Chang, one sheet supplied by Dr. Padamsee (Cornell) and one sheet from Dr. Kneisel (TJNL). Although the material came from different lots we experienced very little differences or difficulty in the flow of the material during our spinning operations. We want to express our thanks for their material. With the recommendation of Dr. Padamsee of Cornell, an attempt was made to spin a laminated sheet of copper and niobium. The objective behind this attempt was to lower cost of the material by using a copper/niobium laminate. A $1/16$ " thick niobium sheet was laminated to a $1/16$ " copper sheet in a vacuum furnace. An

attempt was made to spin a single-cell cavity from this sheet. However after completing 50% of the single-cell, it appeared that the materials were separating, due to incomplete bonding of the two materials in some regions. The spinning operation was discontinued.

This experiment showed us that the composite niobium/copper sheet spun much more easily than pure niobium. If this laminated material become available in the future, it would open new avenues of cost reduction.

Another technical difficulty uncovered in Phase I involved the process of spinning itself. Metal spinning on a manually controlled machine is an art form entirely dependent on the skill and knowledge of the spinning machinist. In order produce consistently reproducible cavities on a production basis CNC equipment must be utilized.

Conclusions:

1. Single-cell cavities can be successfully spun using parameters and techniques developed in this Phase I research. No appreciable work hardening takes place in the niobium material during the spinning process. Wall thickness uniformity can be maintained in the single-cell cavities.
2. There are no insurmountable barriers to successfully spinning three-cell niobium cavities. In order to spin multiple cell, two or three cell niobium cavities, the difficulty in spinning the material in the iris area must be overcome. New tools must be developed and speed better defined to achieve uniformity in wall thickness and prevent tearing of material during spinning of the iris area.
3. The use of hydraulically powered manual spinning lathes while appropriate for initial data gathering activities, is not appropriate for production spinning of the niobium cavities. Thus for further investigation the use of a programmable numerical control (PNC) spinning lathe will be required.
4. One of the problems experienced in Phase I was the difficulty in controlling the wall thickness of the cell cavity on the hydraulic spinning lathe. Each time there was a tool change, the work piece had to be removed and a blank spinning mandrel had to be used to reset the template and adjust the spinning tool. Again this problem can be overcome with use of a numerically controlled spinning lathe with a tool changer.

Recommendations:

1. Continuing the technical approach of Phase I, further investigation utilizing information and results gathered in Phase I is appropriate. Building on the results of Phase I, removable spinning mandrels could be designed and fabricated along with spinning tools and templates for the fabrication of two-cell cavities. After successful spinning of two-cell cavities, information and spinning parameters could be used to design removable spinning mandrels, spinning tools and templates for the fabrication

of three-cell cavities. These implements will then be used to repeatedly spin three-cell niobium cavities.

2. After reviewing the results of our experiences spinning niobium material during Phase I, the successful spinning of multi-cell cavities in Phase II is within our reach. We realized that using a hydraulic spinning lathe utilizing a template trace control makes it very difficult to control a uniform wall thickness, especially when there are three tool changes. In order to spin a multi-cell cavity successfully, we recommend a Programmable Numerical Control (PNC) spinning lathe with a four tool changer and a blank support plate which will enable us to produce a multi-cell with uniform wall thickness. The PNC will also allow us to produce cavities in a repeatable production mode.
3. With the latest PNC spinning equipment available we believe that we can make spinning niobium cavities a production manufacturing activity. Meyer Tool and Superior Spinning have successfully spun a single-cell and have made great strides towards spinning a two-cell cavity. Building on the knowledge gained in Phase I, removable spinning mandrels and additional spinning tools could be designed and made for multiple setups in the spinning process. With the PNC spinning machine, the spinning in process will be developed to constantly achieve uniform wall thickness in the niobium material with a smooth surface finish without inclusions or tears.