STUDIES OF ALTERNATIVE TECHNIQUES FOR NIOBIUM CAVITY FABRICATION*

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Abstract

Alternative fabrication techniques for superconducting radio frequency (SRF) cavities are being investigated. The main goals are to reduce cavity fabrication costs and expand possibilities for advanced cavity designs. At present, SRF cavities are fabricated via deep drawing of parts from sheet material and electron beam welding (EBW) to join the parts together. EBW produces welds of high quality, but the procedures are costly and time-consuming. Alternative technologies being explored include tungsten inert gas (TIG) welding of Nb, hydroforming of Nb, and electron-beam free form fabrication (EBFFF) of Nb. If techniques can be developed which do not degrade the Nb purity, TIG welding could reduce or eliminate the need for EBW. Hydroforming could also be an alternative to deep drawing and EBW. As has been demonstrated by several other groups, complete cavities can be hydroformed from Nb tubes in one step using internal pressure and outer dies. Hydroforming of cavities in an industrial setting is presently being explored. EBFFF is a new technique for forming parts from wire stock with an electron beam. Though it may not be suitable for fabrication of a complete cavity, EBFFF could be used to produce tubes for hydroforming or parts for drift tube cavities. Additionally, the possibility of producing single crystal tubes using EBFFF is being explored.

INTRODUCTION

Large accelerator projects and possible applications outside the science community are fueling the interest in methods to reduce the capital cost of SRF cavities. Techniques are being investigated to decrease fabrication costs for the production of SRF cavities, as well as infrastructure requirements. Three areas of research presently being explored at Michigan State University (MSU), in collaboration with Fermi National Accelerator Laboratory (FNAL), are high-purity TIG welding, hydroforming, and EBFFF.

In addition to EBW being an expensive and time-consuming step in cavity fabrication, EBW equipment is a significant investment, requiring skilled operators. If it can be done without introducing impurities, conventional TIG welding could be used to weld niobium parts more economically.

Hydroforming is another alternative to EBW. Hydroforming would simplify cavity fabrication and greatly reduce manufacturing costs. Laboratory research has shown that SRF cavities can be formed using internal pressure to deform extruded tubes, and that hydroformed cavities perform well in RF tests [1]. Industrial hydroforming could benefit large-scale accelerator projects and open up additional applications for SRF.

EBFFF is presently used to fabricate complex shapes from expensive materials. This technology is used for titanium, tantalum, and stainless steel parts; the same technique could prove valuable for Nb cavity fabrication.

HIGH-PURITY TIG WELDING

Electron-beam welding of niobium is done in a high vacuum environment, which prevents degradation to the purity of the material, measured by the Residual Resistivity Ratio (RRR). EBW is one of the more costly and time-consuming procedures used in cavity fabrication. TIG welding is routinely used for joining of stainless steel parts. Conventional TIG welding is done in air, which allows some impurities to diffuse into the heated material during welding. If it could be done without degradation of the purity of the Nb, TIG welding could be used for cavity fabrication instead of EBW. TIG welding could be used for both cavities and end assemblies. Techniques for TIG welding in a sealed chamber with an inert gas environment were developed for this study in order to minimize contamination of the weld zone.

Initial studies were done using a “bubble-chamber” made from plastic bag stock. The bubble chamber was used for TIG welding of an S-band single-cell cavity of the TTF shape [2]. RF test results for this cavity and an EBW cavity of the same shape are shown in Figure 1. During vertical testing, optical diagnostics were used to view quench locations on the cavity. Camera images showed no helium boiling along the equator or iris welds. Bubbling from the cavity quench was observed along the cell wall. This indicates that the defects in the cavity were not related to inclusions in the weld (contamination from the TIG tip), but could be from impurities in the bulk (contamination from weld environment). Although the performance of the TIG-welded cavity was not as good as that of the EBW cavity, the results were encouraging enough to motivate the development of a more advanced TIG welding system. Note that, for both cavities, the quality factor was limited by losses in the stainless steel flanges due to the short beam tube length. As can be seen in Figure 1, the Q of the EBW cavity improved when the copper gaskets were replaced with Nb disks.

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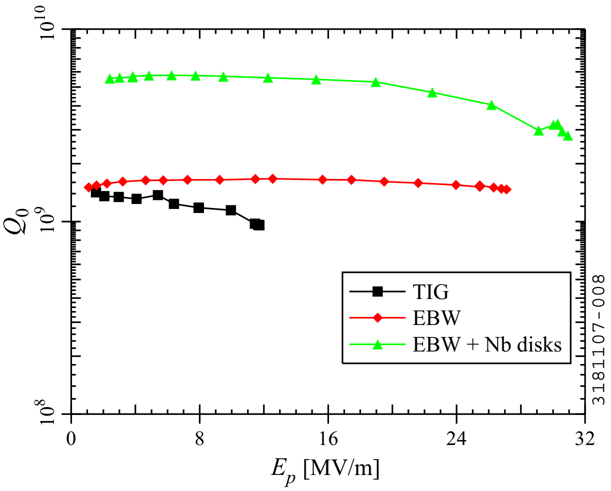

Figure 1: RF tests on 2.45 GHz cavities comparing TIG welding in a bubble chamber and EBW.

A welding chamber was made from an existing vacuum vessel for additional TIG welding studies. Ports for gloves were added to the midsection; a window was added in the upper section. An argon gas circulation system was integrated into the chamber to provide filtered argon for purging and circulation during welding. An oxygen analyzer was used to monitor the chamber environment. Figures 2 and 3 show the assembled TIG chamber and the gas circulation system.

Welding Procedure

The Nb parts are cleaned, etched (buffered chemical polish), rinsed, dried, and bagged. They are placed in the chamber in their open bags. The chamber is sealed and pumped out. The glove ports and the window are sealed off from the outside and connected to the chamber during the pump-down, so that they do not have to withstand a pressure differential. The chamber is pumped to a pressure of ~50 millitorr and then backfilled to atmospheric pressure with argon gas. The chamber is then pumped out a second time and again backfilled with argon. The outside of the glove ports and window are then valved off and the covers are removed. The residual oxygen sensor is used to check the background oxygen concentration.

Figure 2: Chamber for high-purity TIG welding.

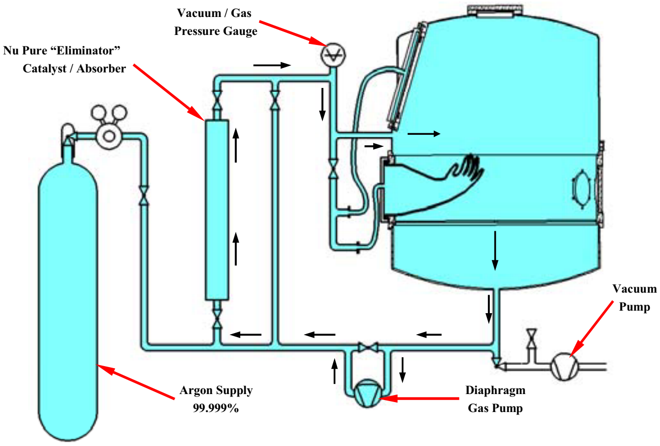

Figure 3: Schematic showing argon gas circulation in the TIG chamber.

Using the glove ports, parts are removed from the plastic bags, positioned, and welded as in a conventional TIG welding operation. Stainless steel mesh gloves are worn over the rubber gloves to dramatically reduce thermal radiation heating of the black rubber during welding. Argon is fed in through the TIG torch at variable rates (the highest flow rate being ~30 liters per minute) and the additional gas is vented to maintain atmospheric pressure in the chamber. After the welding is completed, the argon flow is turned off and the vent valve is closed. When the parts have cooled, the chamber is opened and the parts are removed.

Welding Results

The initial samples showed large degradation in RRR values. The RRR degradation was correlated with the measured oxygen concentration. The initial tests had a high oxygen background in the chamber, resulting from a leak in the main chamber seal. After the seal was repaired, background readings of 30 ppb (O_2) could be obtained. Even after the leak was repaired, welded samples still showed degradation in their RRR, and also showed signs of embrittlement. The degradation was thought to be due to surface impurities of the welded material and gasses from the chamber surfaces diffusing into the heated Nb. In an attempt to eliminate this contamination, a high flow argon purge was added. Improved RRR values were obtained with samples welded in this configuration. Table 1 shows RRR data of samples welded under different conditions.

Future Work

Additional welding of samples will be done and RRR values will be measured. Multiple vendors will be used to verify results. A 1.3 GHz single cell cavity will be welded in the TIG chamber, using existing dies to form the half-cells. All of the joints will be TIG welded. The cavity will be etched, rinsed, and RF tested. High-purity TIG welding will also be applied to end group assemblies.

Table 1: Measured RRR of niobium samples after TIG welding in the chamber. The uncertainty in the measured RRR values is estimated to be ±20%. Samples 1 through 4 were welded before the leak in the chamber seal was repaired. All samples were made from the same parent material; the measured initial RRR for a control sample was 279.

Sample	Etch	Purge gas	Measured O_2 conc. (ppb)	RRR
1	no	none	~20 000	9
2	yes	none	~5 000	10
3	yes	low flow	~500	57
4	yes	low flow	~400	24
5	no	high flow	~30	209
6	yes	high flow	~30	277
7	yes	high flow	~30	274

HYDROFORMING

The development of weld-free cavities is being investigated as a cost reduction measure. Research has already shown that niobium tubes can be formed into multi-cell cavities using hydroforming and swaging techniques with good RF performance as compared to EBW cavities [1]. Commercial bellows manufacturers in the USA can produce copper structures similar in shape to elliptical cavities using inexpensive forming techniques used for bellows, as shown in Figure 4. By using internal pressure and external dies, a seamless Nb tube could be formed into a complete cavity in one or two steps. The research was initiated by going directly to industry to begin developing forming parameters, using standard hydroforming equipment. The company used in this study is a well-established bellows manufacturer with over 100 years of experience.

Production of multi-cell 3.9 GHz cavities will be studied with industrial partners, as well as other laboratories such as DESY. The prototyping will be done using Cu initially and then high RRR Nb. The weld-free Nb cavities will be etched, rinsed, and RF tested to check performance.

Figure 4: Industrial hydroforming of copper tubes.

Copper Prototypes

Commercial OFHC Cu tubing was used for initial prototyping. Some results are shown in Figure 5. The Cu tubing was seamless, with an initial wall thickness of 3.175 mm. Prior to forming, the tubes were annealed at 700°C for 1 hour, increasing the elongation to ~50%; annealed Cu approximates the elongation properties of high purity Nb better than work-hardened Cu. Initial hydroforming was done using only centering pins to define the iris locations. Walls were formed nearly perpendicular to the tube axis. Six-cell cavities were easily formed with one single hydroforming operation at ~3000 psi. The choice of six cells was for ease of die development and measurement of cell concentricity, but cavities with more than six cells should be possible. Multiple prototype cavities were made, while increasing the deformation (radial elongation) from the initial tube diameter. As the deformation increased, more thinning was observed in the equator region. “Orange-peel” or surface roughness was observed to increase with increasing deformation. To ensure cavity integrity under vacuum loading, forming was stopped once the equator material thinned to 2 mm. An initial tube of 57.15 mm inner diameter was hydroformed to an equator diameter of 123.83 mm. Increasing the wall thickness of the initial tube could allow further forming.

Figure 5: Samples of hydroformed copper cavities.

Swaging or grooving is a technique that can be used with hydroforming to decrease the required outward deformation. By using a two-step operation in which inward deformation is applied, the starting tube diameter can be increased. The larger tube is grooved inward along the tube length, as shown in Figure 6. The grooves ultimately become the irises of the finished cavity. After grooving, the cavity would be hydroformed, pushing outward on the tube, until the final shape is reached. Swaging produces thinning at the irises, while hydroforming thins the wall in the equator regions.

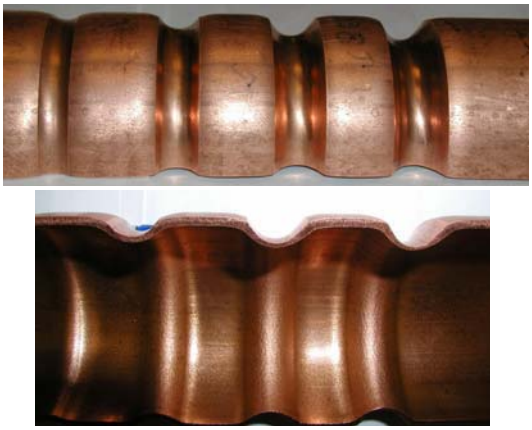

Figure 6: Samples of swaging or grooving of Cu tubes.

Future Work

Additional work will be done with Cu tubes to develop external dies to more accurately define the cavity shape. Once the die parameters are set, Nb tubes will be formed, first for single-cell and two-cell structures. Seamless Nb tubes in the lengths required for multi-cell hydroforming are not yet commercially available. Different tube fabrication techniques will be investigated to produce seamless tubes with the required mechanical properties in a cost-effective manner.

Extruded seamless tubes are commercially available in short lengths, with recrystallized microstructure suitable for hydroforming. Single cell cavities have been successfully formed from extruded tubes [1]; however, longer tubes would be required for multi-cell cavities. Some possible approaches to tube production are dynamic flow forming and single crystal tubes.

Dynamic flow forming is a technique used to produce long thin-walled tubes such as flagpoles. A thick tube is the starting point; the inner diameter is cut to fit a long inner mandrel. Using external rollers and increasing radial pressure, the thick wall is squeezed down the inner mandrel, forming a long thin-walled tube. The final tube's microstructure has elongated grains in the flow direction. Long seamless Nb tubes have been formed using this technique [3]. The concerns with this method are the microstructure of the tubes and the capital cost of the starting form. The microstructure would not be suitable for hydroforming, but recrystallization via heat treatment of the formed tube could provide the required elongation properties.

Single crystal tubes would be an ideal solution because of the large elongation properties. Different concepts are being investigated to produce a "seamless" single crystal tube. One approach is to start with a thick single crystal plate and roll the crystal into a thin sheet, which is then rolled into a tube. Studies have shown that single crystals with certain orientations can be rolled and annealed to form single crystal sheets without recrystallization [4]. Single crystals with low strain can be electron-beam welded without recrystallization in the weld region [5]. Production of "seamless" single crystal tubes is being studied at FNAL via this approach: rolling a single crystal ingot, annealing, rolling into a tube, reannealing, and electron-beam welding the seam along a low angle boundary.

EBFFF

MSU is also investigating the potential of seamless tube fabrication using an electron-beam/wire building technique called Electron Beam Free Form Fabrication (EBFFF). Sciaky, Inc. (Chicago, IL) has developed this procedure to produce complex shapes with exotic materials using wire-feed in conjunction with electron-beam melting. This technique has been used for materials that are costly and require long lead times to produce stock material in required dimensions. Wire is mounted within the EBW chamber on a spool that is aligned to feed into the electron beam. Using the triple axis control system, the EBW gun can be programmed to trace out complex patterns. The gun melts the feed wire and moves along the programmed shape. The molten wire is deposited and solidifies, forming the desired shape, as shown in Figure 7. This technology has been successfully used for titanium, tantalum, and stainless steel.

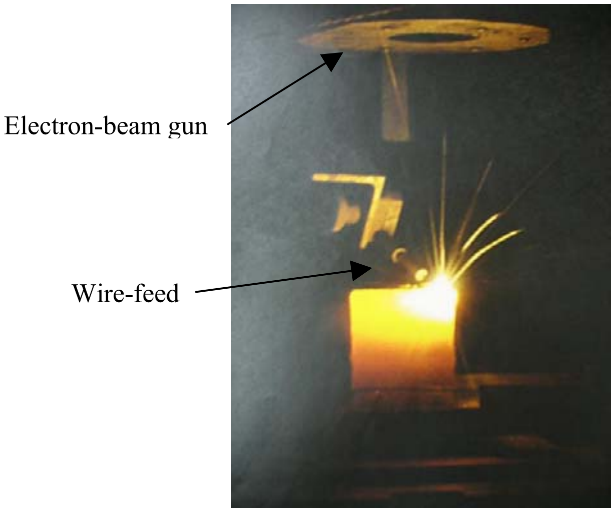

Figure 7: Electron-beam free form fabrication (EBFFF) at Sciaky, Inc. (Chicago, IL).

The goal will be to produce tubes appropriate for hydroforming and determine the range of mechanical properties that can be achieved. MSU will also explore the possibility of single crystal tube fabrication via deposition of the niobium tube onto a single crystal substrate. As the wire is melted onto the base material, the solidified material should have the same microstructure as the base material. As the material is built up, each new layer will solidify onto the last one, possibly forming the same microstructure. If the technique is able to produce suitable Nb tubes, the tubes can be hydroformed into cavities using laboratory or industrial techniques. The study will also explore the potential for applications beyond tube fabrication, such as production of complex Nb shapes (higher-order mode couplers, for example) and Nb cavity repair.

Initial Results

Two Nb tubes have been made using EBFFF. Grade 1, 2.36 mm diameter Nb wire was used as the initial feed stock. The wire was wound onto an existing spool in Sciaky's EBW chamber. Both tubes were formed using the same beam parameters and program. The tubes were constructed with a 70.5 mm outer diameter and a height of 33.2 mm. Both tubes had a final wall thickness varying between 7 mm and 8.5 mm. The first tube, shown in Figure 8, was formed onto a polycrystalline substrate (grains size ~50 um). The second tube was formed onto a single crystal substrate. Samples were EDM cut from the tubes and the crystal orientations were measured along the tube length, as shown in Figure 9. The first tube's microstructure was polycrystalline, with random orientations matching the parent material. The second tube's microstructure remained single crystal up to ~10 mm from the substrate. Beyond that distance, grain rotations were observed. These results show that the concept is viable, but more research is needed to optimize the deposition and cooling parameters.

Figure 8: Niobium tube fabricated on polycrystalline substrate from wire using EBFFF.

SUMMARY

Alternative fabrication techniques show great promise for the fabrication of SRF cavities. These techniques not only show cost savings potential, but also are suitable for industrial production. Development work in an industrial setting grows confidence outside the laboratory, which should lead to lower fabrication costs and open avenues for future applications of SRF technology.

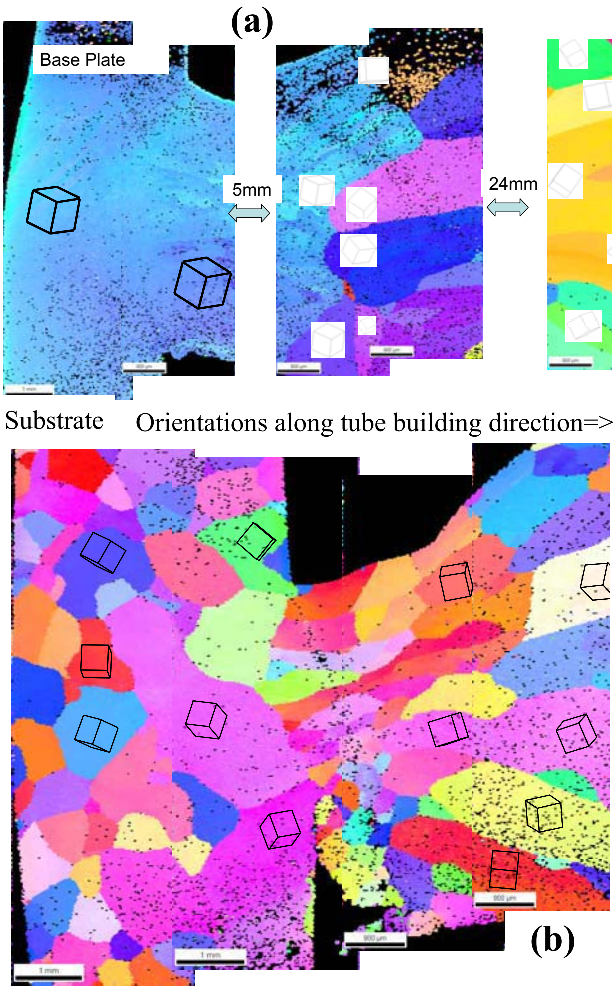

Figure 9: Crystal orientation imaging of niobium tubes fabricated using EBFFF: (a) tube formed onto a single crystal substrate, showing single crystal growth near the base; (b) tube formed onto a polycrystalline substrate, showing polycrystalline microstructure.

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