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Development of Seamless Niobium Cavities for Accelerator Applications*

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Abstract

Superconducting niobium cavities for application in particle accelerators are usually fabricated by standard techniques such as forming of subcomponents by deep drawing and joining by electron beam welding. Even though these techniques are being used successfully in many larger-scale accelerator projects and improvements in accelerating gradients have been achieved over the last several years, there are often still problems with making defect-free electron beam welds. In addition, the manufacturing costs for such devices are significant and a drastic reduction in production costs is a necessary condition for future very large scale applications in, e.g., linear colliders.

Seamless cavities made by spinning from a single sheet of material will dramatically reduce the fabrication costs and eliminate any problems associated with electron beam welding.

The fabrication technique for seamless niobium cavities has been developed over the last few years at INFN LNL and several prototype single-cells of different material thickness and purity have been manufactured as well as a 5-cell cavity. Results from tests on these cavities after application of surface treatment techniques, such as buffered chemical polishing, "barrel polishing" and high temperature heat treatments, are discussed in this contribution. Q-values as high as 10^{11} and accelerating gradients up to $E_{acc} \approx 30$ MV/m have been measured.

1 INTRODUCTION

Superconducting radio-frequency (SRF) technology has been applied successfully in the last decade in several large-scale particle accelerator projects around the world such as TRISTAN, LEP, HERA and CEBAF. Future applications in B-factories, proton accelerators, linear colliders for electrons/positrons or muons and in higher-power free electron lasers are being pursued seriously in various laboratories. The reasons for this continued interest in SRF technology are elimination of limiting phenomena and application of improved processing and handling techniques resulting in better cavity performances. However, future projects, which involve hundreds or thousands of meters of superconducting structure, demand a significant simplification of procedures to achieve even better performance than has been required for the presently operating accelerators. One of such simplifications could be a replacement of the typical cavity fabrication technique of electron-beam-welding precision-machined niobium parts into an accelerating cavity by the fabrication technique of seamless cavities. In the following sections we will describe the technical approach pursued for several years at INFN LNL and will report on the encouraging cavity performances achieved after various processing steps mainly performed at Jefferson Lab.

2 CAVITY FABRICATION

The idea of manufacturing seamless cavities is not new, because this technology offers several potential benefits:

- elimination of electron beam welds
- streamlining of Quality Assurance (QA) procedures
- significant reduction in manufacturing cost
- reduction of necessary infrastructure for mass production because of "speedy" manufacturing

Several attempts have been made in the past to form cavities without welding either by hydroforming [1,2] or by explosion forming. Hydroforming was only successful for copper as the base material and needed two intermediate annealing steps; it failed when niobium was used, mainly because of structural non-uniformity of the niobium tubes. Despite these earlier setbacks, groups at DESY [3] and at Saclay [4] are pursuing this technology—backed by computer modelling—with initial encouraging results. Both laboratories succeeded in bulging monocell resonators, and accelerating gradients around $E_{acc} \approx 20$ MV/m were reached.

Initial tests on explosive formation of cavity shapes showed also discouraging results due to the inevitability of intermediate annealing steps. Therefore the work at INFN LNL concentrated on developing the well-known spinning technique for manufacturing of seamless niobium cavities.

The process developed at INFN LNL involves basically two steps: in the first step a tube is formed from a sheet of material either by spinning it onto a frustrum-shaped mandrel of proper dimensions or, more recently, by deep drawing a tube with a diameter equal to the diameter of the cavity equator; in the second step the tube is then spun onto a demountable die of the true shape of the cavity, which is either made of precision machined nylon or

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stainless steel. When the spinning process is completed—it takes typically one hour to spin a single-cell cavity and the better part of a day to spin a 5-cell cavity—the mandrel is extracted by collapsing the "keyed" elements of it. The main advantage of this process lies in the possibility of avoiding intermediate annealing and even multicell cavities can be cold formed straightforwardly from a planar disc. More details can be found in ref. [5-7].

Figure 1 is a snap shot of the incomplete cavity during the spinning. Figure 2 is a collection of single and 5-cell cavities tested during this investigation.

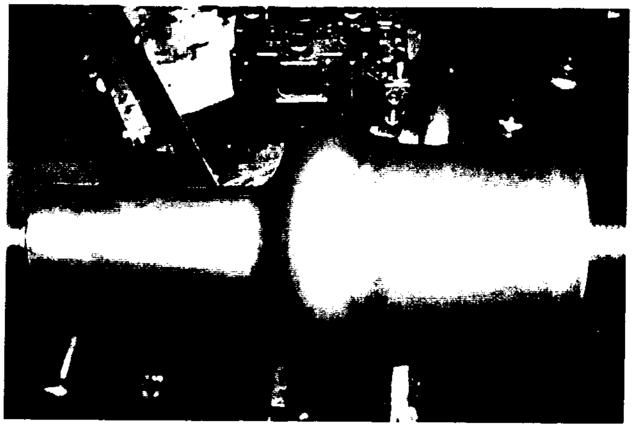


Figure 1: Spinning of a single-cell cavity, example Cu

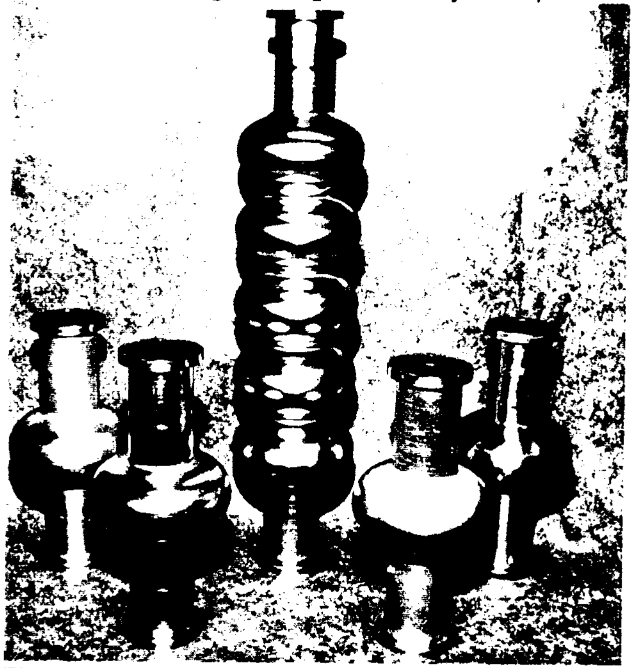


Figure 2: Selection of spun cavities used in this investigation

In total six single-cell cavities and one 5-cell cavity were tested during the course of this investigation. Cavities P1, P2, P5 and P6 were spun from high-purity niobium (RRR ≥ 250), whereas cavities P3 and P4 were made from reactor-grade niobium. The first 5-cell cavity P5-1 was again manufactured from high-purity niobium. Cavity P1 was originally fabricated for CERN and tested there. A few tests were performed at Jefferson Lab afterwards after mechanical grinding.

3 RESULTS AND DISCUSSION

After the spinning was completed at INFN LNL, beam pipe sections and flanges were electron beam welded to the cavities at Jefferson Lab [8].

Subsequently, standard processing procedures such as buffered chemical polishing (bcp) followed by high pressure ultrapure water rinsing for up to 2 hrs and clean room assembly were applied. In the case of cavity P2, which was the first cavity sent to Jefferson Lab for investigation, a series of small subsequent material removal steps were carried out in order to study the effect of the removal of the surface damage layer on cavity performance as measured by the Q_0 vs. E_{acc} at 2K. The results of these tests are shown in figure 3. As can be seen, a continuous improvement of E_{acc} is achieved by etching away more and more material from the surface, indicating that the spinning process introduces a rather deep damage layer in the material. The steep decrease of the Q-value beyond a certain field is not caused by the onset of field emission loading. This field is shifted towards higher values with deeper material removal. The additional resistance represented by this Q-degradation is, in most cases, proportional to $E_{acc}{}^{n}$ with $4 \leq n \leq 8$ and is not understood.

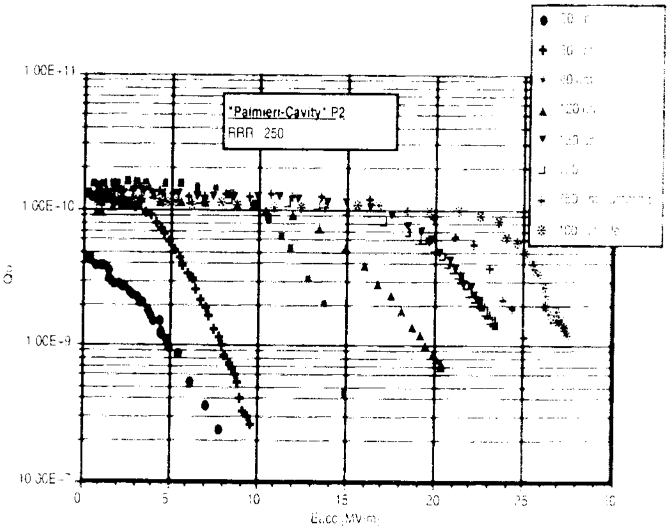
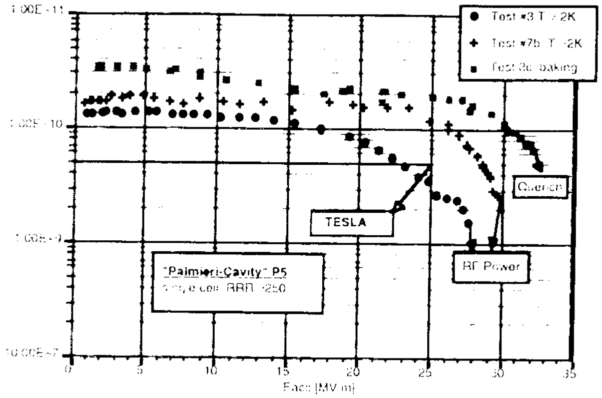


Figure 3: Dependence of cavity performance on removal of surface layer; data from single-cell cavity P2 (He = Helium processing)

In figure 4 the final performance of cavity P5 is plotted; the cavity "quenched" at $E_{acc} \approx 33$ MV/m.

However we noted that the spinning process left a large amount of narrow cracks in the material at the irises near the beam pipes as shown in figure 5. Mechanical removal of these cracks by either grinding with an abrasive or by "barrel polishing" [BP] [9] seemed to significantly reduce the severe Q-drop at high fields.



Test #3: 234 µm bcp
Test # 6b: tumbling for 100hrs,80 µm bcp,heat treatment at 900C for 1 1/2 hrs, 60 µm bcp,grinding of cracks at beam pipe, 50 µm bcp
Test #7c: 20 µm bcp, baking at 115 C for 40 hrs "in situ"

Figure 4: Best Performance of Cavity P5

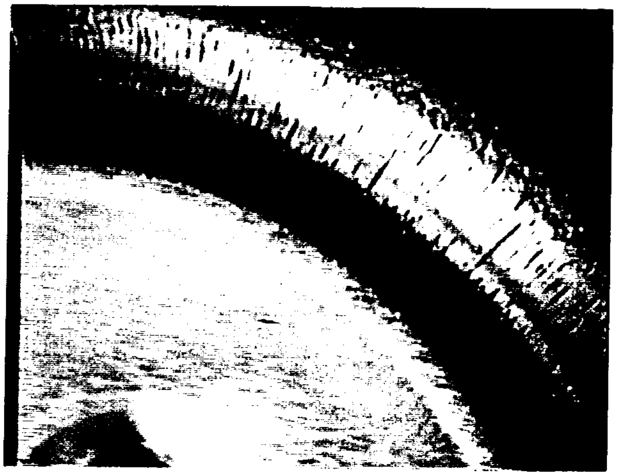


Figure 5: Cracks in the niobium located at the beam pipe iris.

The best performances of all the tested cavities are listed in Table 1; in several cases a heat treatment was applied either for hydrogen degassing and stress relieving purposes (T ≈ 800—900 C) or for post-purification in order to increase the thermal conductivity (T≥ 1200 C) of the material. No major improvements beyond the effect of material removal were seen, however. In several cases also surprisingly low residual resistances in the order of 2 - 3 nΩ were measured corresponding to Q-values ≥ 10^{11}. The 5-cell cavity P5-1 initially was limited by a quench at E_{acc} ≈ 11.5 MV/m in the π - mode and from measurement of the other pass-band modes it was concluded that the defect most likely was located in one of the end-cells. By analyzing the results of the measurements of the other pass-band modes it also became clear that the three inner cells of the 5-cell cavity were performing much better than the end-cells; the center cell quenched at about 25 MV/m and the two neighboring cells sustained at least a field of 17 MV/m. An attempt to improve the cavity performance by mechanical grinding of the end-cells has not been successful yet and further work is needed.

Table 1: Best Results Achieved with the SeamlessCavities (RG = reactor grade, RRR= high purity, HT=heating,BP= barrel polishing)

CAV	Nb	Q_{res} [10^{10}]	E_{acc} [MV/m]	Comments
P1	RRR	0.3	25	40 µm grinding, insufficient bcp
P2	RRR	>9	28	400 µm bcp, BP,HT≈1200 C
P3	RG	>10	16.5	200µm bcp,BP HT≈1300 C, 100 µm bcp
P4	RG	>10	15	BP,100 µm bcp HT≈1200 C 250 µm bcp
P5	RRR	>10	33	230µm bcp,BP HT≈900 C 280µm bcp
P6	RRR			low Q,needs work
P5-1	RRR	>7	11.5	120 µm bcp end cells need work

4 SUMMARY

This investigation has shown that the fabrication of seamless cavities with its potential benefits of lower cost at high performance levels is feasible. Future work has to concentrate on eliminating some of the observed drawbacks such as the cracks in the material, the rather large amount of material removal necessary for good performance, non-uniformity in material thickness, and, for multi-cell cavities, the need for a stringent control of tolerances to maintain good electric field flatness. Cavity P6 was manufactured from a deep drawn tube and a significant reduction in material defects and much improved material uniformity were observed. This seems to be the right direction for future work. In addition it seems quite prudent that the skillful manual spinning process so far applied for the fabrication of these cavities needs to be transfered to mass production equipment.

5 REFERENCES

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