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EVALUATION OF SINGLE-CELL CAVITIES MADE OF FORGED INGOT NIOBIUM AT JEFFERSON LAB*

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Abstract

Currently, fine grain niobium (Nb) (grain size ~ 50 μm) and large grain Nb (grain size of a few cm) are being used for the fabrication of superconducting radio frequency (SRF) cavities. Medium grain forged ingot with grain size of a few hundred μm may be beneficial for cost-effectiveness as well as providing better performance for future SRF-based accelerators. Forged ingot Nb with medium grain size is a novel production method to obtain Nb discs used for the fabrication of superconducting radio frequency cavities. We have fabricated two 1.5 GHz single cell cavities made from forged Nb ingot with a residual resistivity ratio of ~ 100. The cavities were chemically and mechanically polished and heat-treated in the temperature range of 650-1000 °C before the rf test. One of the cavities reached an accelerating gradient of ~34 MV/m with a quality factor $Q_0 > 10^{10}$, while the second cavity was limited at 14 MV/m, likely due to a weld defect at the equator.

INTRODUCTION

Future accelerator projects have a high demand for high-performance and cost-effective superconducting radio frequency (SRF) cavities. SRF cavities made from fine grain (FG) (ASTM ~ 5-7) and large grain (LG) (grain size ~ cm) have been already installed in several accelerator facilities [1–3]. The production of FG niobium requires multiple steps and stringent quality assurance methods, whereas the LG niobium can be directly sliced from an ingot greatly simplifying and lowering the production cost of bulk Nb discs [4]. Even though the performance of cavities fabricated from LG Nb are comparable or better than that of cavities made from FG Nb, the accelerator community is reluctant to use LG Nb due to nonuniform mechanical properties arising from the large grains with different orientations. This feature complicates compliance with pressure vessel regulations in some countries. Twenty-four 1.5 GHz 5-cell cavities made of LG Nb have been recently built by Research Instruments GmbH, Germany, for the C75 cryomodule refurbishment program at Jefferson lab C75, with 16 of those cavities already operating in the CEBAF tunnel [3, 5].

To minimize the shape variation during the deep drawing process, while keeping the production cost low, medium grain (MG) Nb with the grain size of several mm was produced by forging and annealing a large grain billet [6]. The process requires fewer steps than the manufacturing of FG Nb while producing more homogeneous grains with the mechanical properties required for deep drawing of half cell for SRF cavities [7]. Two 1.3 GHz single-cell cavities were fabricated at KEK using high-purity, residual resistivity ratio (RRR) > 300, MG Nb and one of them reached an accelerating gradient, E_{acc}, of 38 MV/m at 2 K [8]. Further material cost reduction could be realized with lower purity Nb, because of fewer ingot melting cycles. In this contribution we describe the fabrication, processing for two 1.5 GHz single cell cavities made of medium-purity MG Nb and present their cryogenic cryogenic rf test results for two 1.5 GHz single cell cavities made of medium-purity MG Nb. Measurements to characterize the flux expulsion as well as the rf performance with respect to annealing temperature and surface preparations were part of this study.

CAVITY FABRICATION AND SURFACE PREPARATIONS

The MG Nb cavity development at Jefferson Lab is being carried out as R&D related to the C75 CEBAF cryomodule refurbishment program [9]. Two single-cell cavities of the C75 inner cell shape and labeled C75-SC2 and C75-SC3, have been fabricated from 3 mm thick MG Nb discs of RRR ~ 100, produced by ATI Specialty Alloys, USA. The two discs used for the fabrication of C75-SC3 had been annealed by the Nb vendor at a higher temperature than those used for C75-SC2. The fabrication was done by using conventional methods of deep drawing of the Nb discs and electron beam welding of the half-cells and beam tubes. The shape deviation of the half-cells was inspected with a 3D laser scanner and ~ 63% of the points were within ±0.1 mm from the ideal shape, as shown in Fig.1. This value is consistent with what was achieved with a standard FG Nb discs, using the same dies, and it is better than those achieved using LG Nb.

After the fabrication, the cavities received ~120 μm of inner surface removal by electropolishing (EP) followed by vacuum annealing at 650 °C for 10 hours. The cavities again received 25 μm inner surface EP. Standard procedures were followed to clean the cavity surface in preparation for an rf test: degreasing in ultra-pure water with a detergent and ultrasonic agitation, high pressure rinsing with ultra-pure water, drying in the ISO 4/5 cleanroom, assembly of flanges with rf feedthroughs and pump out ports and evacuation.

After the first cryogenic rf test, the cavities were baked in-situ at 120 °C for 48 h and re-tested. Afterwards, the cav-

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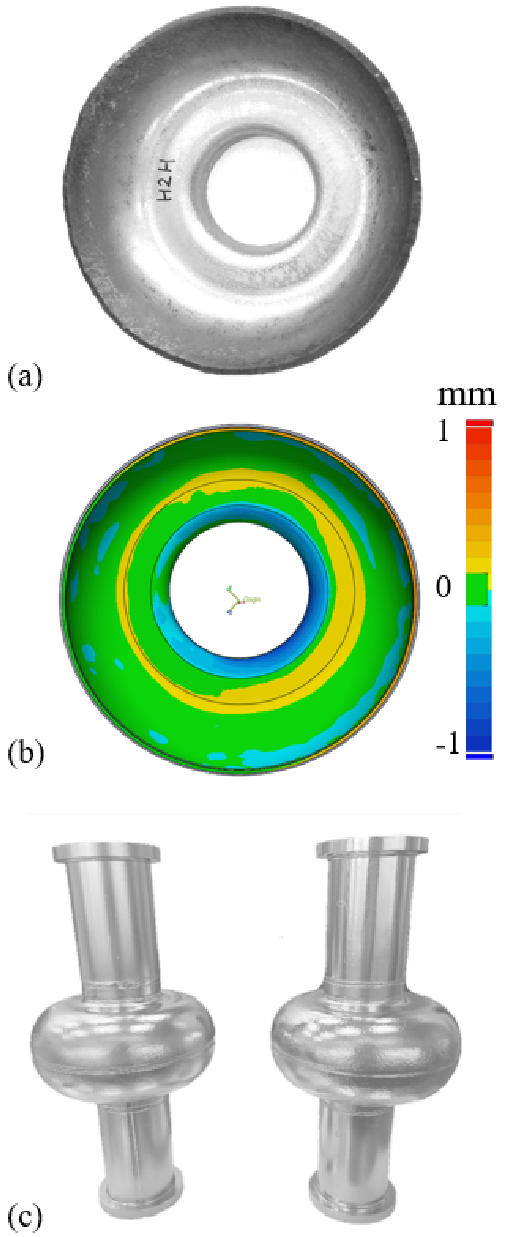

Figure 1: Fabrication of single cell cavities (a) deep drawn half cell, (b) 3D scan of half cell and comparison with design, and (c) final single cell cavities.

ities were subjected to a 2-step centrifugal barrel polishing (CBP) with medium and fine polishing media. This resulted in a mirror-like finish of the inner surface after removing ~60 μm followed by an additional ~30 μm removal by EP. The cavities were then annealed in high vacuum at 800 °C/3h and tested at 2 K for a third time. Finally, C75-SC3 was annealed at 1000 °C/3h and tested a fourth time. The final chemistry was omitted after the last two heat treatments because of using clean Nb caps to cover the flanges inside the furnace.

EXPERIMENTAL SETUP

Three single-axis cryogenic flux-gate magnetometers (FGM) (Mag-F, Bartington) were mounted on the cavity surface parallel to the cavity axis in order to measure the residual magnetic flux density at the cavity outer surface during the cooldown process. Three sensors were placed at the equator, ~ 120° apart. The magnetic field uniformity within the cavity enclosure is ~ ±1 mG. Six calibrated temperature sensors (Cernox, Lakeshore) were mounted on the cavity: two at the top iris, ~ 180° apart, two at the bottom iris, ~ 180° apart, and two at the equator, close to the FGMs. The cavity was inserted in a vertical cryostat and cooled to 4.2 K with liquid helium using the standard Jefferson Lab cooldown procedure in a residual magnetic field of < 2 mG. This procedure results in a temperature difference between the two irises ΔT > 4 K when the equator temperature crosses the superconducting transition temperature (~ 9.25 K), which provides good flux expulsion conditions. The average rf surface resistance was obtained from the measurement of $Q_0(T)$ at a low rf field (B_p ~ 20 mT) from 4.3 - 1.6 K. The $R_s(T)$ data were fitted with the generic expression and methods used in Ref. [10] to extract the residual resistance. The high-power rf measurements were done at 2.0 K, acquiring $Q_0(E_{acc})$.

RESULTS AND DISCUSSIONS

Flux Expulsion

The ratio of the residual DC magnetic field measured after (B_{sc}) and before (B_n) the superconducting transition qualitatively explains the effectiveness of the flux expulsion during the transition. A value of B_{sc}/B_n = 1 represents the complete trapping of the magnetic field during cooldown, whereas a flux expulsion ratio of ~1.65 at the equator would result from the ideal superconducting state. Figure 2 shows the result of flux expulsion measurements on cavity C75-SC3 after annealing at different temperatures. The flux expulsion behavior is poorer compared to cavities made from LG Nb [11] but comparable to that of cavities made from FG Nb subjected to 800 °C heat treatment [12, 13]. No significant improvement in flux expulsion was observed even after the 1000 °C heat treatment. The flux trapping sensitivity, the increase in residual resistance per mG of trapped flux was measured to be 0.67 nΩ/mG for C75-SC3 after 1000 °C/3h heat treatment.

RF Results

Figure 3(a) shows a summary of the rf test results for C75-SC2. The cavity was limited by a quench at 14 MV/m. The quench location was found to be at the equator, by using oscillating super-leak transducers (OSTs) [14]. An optical inspection after the 2^{nd} rf test showed an overall roughness and a possible weld defect at the quench location. Surprisingly, the quench location did not change in the 3^{rd} rf test, after CBP and EP, even though the optical inspection of the

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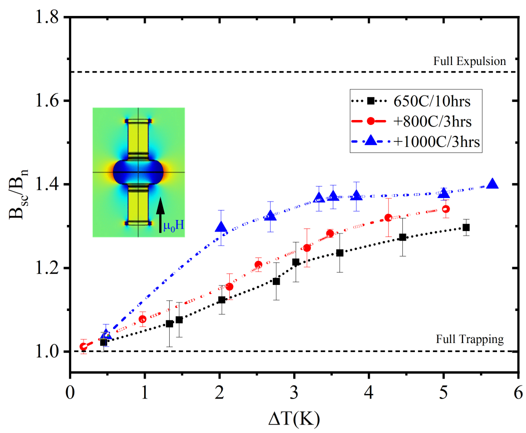

Figure 2: Flux expulsion ratio, B_{sc}/B_n as a function of temperature difference $\Delta T = (T_{top-iris} - T_{bottom-iris})$ for cavity C75-SC3, after successive heat treatments. Inset shows the COMSOl simulation of full flux expulsion of perfect superconducting cavity.

quench location showed a much smoother surface and no large defects as shown in Fig. 4 (c).

Figure 3(b) shows the summary of rf test results for C75-SC3. The first 3 tests were limited by quench whereas the last test after 1000 °C/3h was limited by strong multipacting (MP). The quench location found by OSTs was near the equator and the optical inspection following the 2^{nd} rf test showed an overall rough surface and a feature close to the equator weld as shown in Fig. 4 (b). The quench induced by the MP was observed at the same location.

The cause for the severe MP in the last test of C75-SC3 is not clear and several 5-cell cavities for the 1^{st} C75 cryomodule were limited by the same phenomenon [3,5]. We have changed the shape of a cavity by compressing and stretching the cavity in order to explore if the shape deformation was related to the strong MP. However, the rf tests did not show any significant change in MP behavior after tuning the cavity by up to ~ 20 MHz. To further explore if the MP was due to the contamination, the cavity's rf surface was EP'ed 25 µm and rf test was repeated. During the first power rise the cavity reached 30.3 MV/m and limited by quench. After the quench, the cavity's gradient dropped to 26 MV/m and unable to reach the previous gradient. The fluctuation in magnetic field recorded by FGM mounted on outer surface of cavity was ~ ±1 mG.

As a result of MP, both the accelerating gradient and quality factor degraded. The decrease in quality factor after the cavity quench or multipacting has been observed a few times in cavities made from bulk Nb [15], but extensively seen in multi-metallic cavities [16], likely due to the generation of thermocurrents during cavity breakdowns. A FGM installed at the MP location near the equator showed large magnetic field fluctuations during the breakdown events. The increase in residual resistance was found to be higher than 10 nΩ, which corresponds to about 20 mG of additional magnetic flux trapped in the cavity as a result of cavity breakdown. The residual magnetic field inside the Dewar did not change and it was ~ 1 mG for all tests.

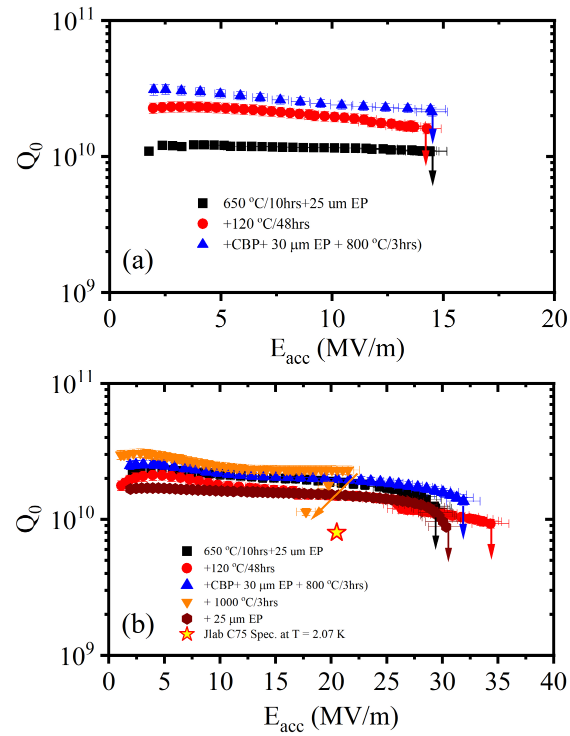

Figure 3: The summary of rf results, $Q_0(E_{acc})$ at 2.0 K after each heat and surface treatments for cavity (a) C75-SC2 and (b) C75-SC3. The vertical arrows represents the rf tests were limited by quench. The rf test for cavity C75-SC3 after 1000 °C/3h was limited by multipacting.

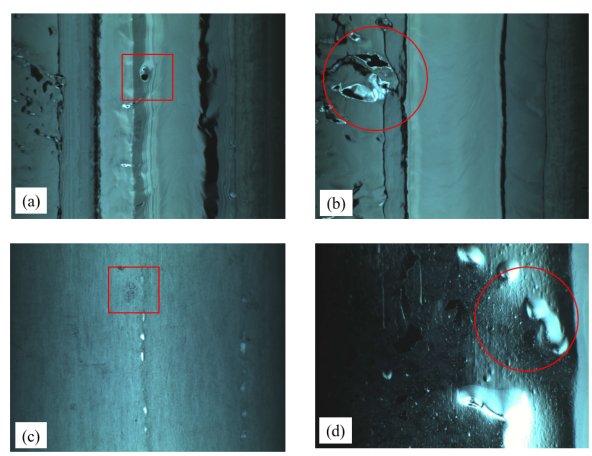

Figure 4: The photograph of the cavity's quench locations: (a) & (b) before and (c) & (d) after CBP and EP for cavities C75-SC2 and C75-SC3 respectively. The marked features are suspected to be the quench locations from OST measurement.

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SUMMARY

We have successfully fabricated, processed and tested two single-cell 1.5 GHz cavities made from medium purity, MG bulk niobium. The cavities made with MG niobium showed poorer flux expulsion and higher flux trapping sensitivity compared to FG and LG niobium [11], likely due to a higher density of dislocation sites, as a result of forging process. To achieve better flux expulsion and lower flux trapping sensitivity, the cavities may require to be heat treated higher than 1000 °C, which however, will negatively impact their mechanical properties. The rf performance of one cavity exceeded the C75 project specification in gradient with high quality factor, when the cavity is cool down in a minimum residual magnetic field. Research Instruments is currently fabricating a C75 5-cell cavity from the same type of material. The cavity will be processed with the same treatment procedures currently followed for all other C75 cavities, made of large-grain Nb, which consists mainly of CBP, EP, and vacuum annealing.

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