MECHANICAL PROPERTIES OF INGOT NIOBIUM CAVITIES*

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Abstract

This contribution presents the results of measurements of the resonant frequency and of strain along the contour of a single-cell cavity made of ingot Nb subjected to increasing uniform differential pressure, up to 6 atm. The data were used to infer mechanical properties of this material after cavity fabrication, by comparison with the results from simulation calculations done with ANSYS. The objective is to provide useful information about the mechanical properties of ingot Nb cavities which can be used in the design phase of SRF cavities intended to be built with this material.

INTRODUCTION

Superconducting radio-frequency (SRF) cavities made of ingot Nb material have shown comparable or better performance than those made of standard fine-grain Nb [1]. Research on this type of material has been pursued by several laboratories and universities throughout the world over the past decade and involved measurements of DC and RF superconducting properties, mechanical properties, thermal properties, field emission properties and chemical analysis of the surface after standard treatments [2, 3].

Mechanical properties of ingot Nb have been measured on samples from uniaxial tensile tests, both at room temperature and at cryogenic temperatures, and from biaxial tensile tests at room temperature [4-7]. Residual stresses have been measured in a half-cell after deep-drawing [8] and a pressure test of a 9-cell cavity up to the breaking point of the material has been recently done at DESY [9]. The large grain size (typically greater than 1×1 cm^2) of ingot Nb material results in "earing" of the half-cells after deep-drawing because of non-uniform deformation of the different grains.

An important step during the cavity design is a structural analysis to insure that no plastic deformation of the cavity occurs under different load conditions. Typically, the worst case is an helium gas over pressurization of the outside of the "warm" cavity at the beginning of a cool-down to 4 K [10]. Finite-element modelling (FEM) computer codes, such as ANSYS [11], are routinely used to perform this analysis and rely on material properties obtained from uniaxial tensile tests of samples which were subjected to similar treatment processes as those applied to SRF cavities.

By measuring the strain, ε, at different locations along the cavity contour as a function of a uniformly applied external pressure, P, one can obtain the Young's modulus and Poisson ratio of the material by fitting the data with the $\varepsilon(P)$ calculated with FEM codes.

*This manuscript has been authored by Jefferson Science Associates, LLC under U.S. DOE Contract No. DE-AC05-06OR23177. The U.S. Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce this manuscript for U.S. Government purposes.
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STRAIN MEASUREMENT

Experimental Setup

A single-cell cavity was fabricated from ingot Nb supplied by CBMM, Brazil (ingot "F"). The Nb blanks were heat-treated at 800 °C/3 h after slicing from the ingot by wire electro-discharge machining and prior to deep drawing. The average wall thickness of the cavity is 3.05 ± 0.07 mm. Six calibrated 120 Ω strain gages were bonded to the cavity surface using M-Bond 200 adhesive (Micro-Measurements, USA). Two gage-packages (EA-06-030-TU-120, Micro-Measurements, USA, gage factor = 2.08) are miniature 90° tee rosettes (0.76 mm gage length) and are bonded ~6 mm from the edge of the iris weld-prep, along the contour, and ~140° from each other. Each package has two gages allowing measuring the strain along azimuthal and longitudinal directions. The other two strain gages (CEA-06-125-UW-120, Micro-Measurements, USA, gage factor = 2.01) are bonded ~11 mm and ~28 mm, respectively, from the edge of the equator weld-prep and ~45° from each other. They measure strain in the longitudinal direction and the gage length is 3.18 mm. Each strain gage is located on a different grain of the Nb cavity. The strain gages bonded to the cavity are shown in Fig. 1.

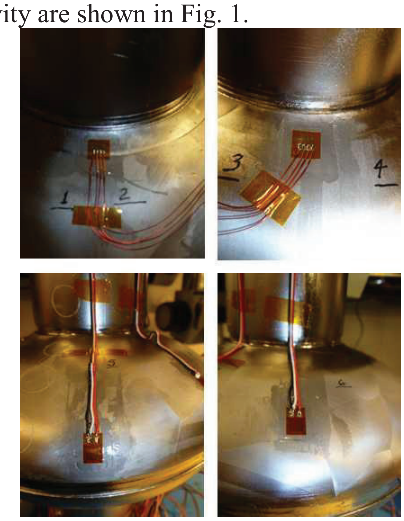

Figure 1: Strain gages' locations.

The cavity is sealed at the beam-tubes with stainless steel (SS) blanks and Indium wire and one of the blanks has an RF feed-through with a coaxial antenna to allow measuring the resonant frequency of the cavity. The cavity inside volume is at atmospheric pressure. The cavity is placed on an Al stand inside a 227 l SS pressure tank (Binks, USA), as shown in Fig. 2. The SS tank has an analog pressure gage, fill and drain ports, 20-wire feed-through and a port for RF cable installation.

The wires from the strain gages are soldered to the feed-through wires and the splices are protected with shrink tubing and liquid tape. The RF cable is bonded to a 70 mm Conflat flange with Loctite 3035 epoxy. The cable connection to the RF feed-through on the cavity is protected with microcrystalline wax. The strain gages are protected with a silicone rubber coating (RTV 3140, Micro-Measurements, USA).

Measurement of the engineering strain is done with the instrument P3 from Micro-Measurements, USA, which connects each set of three wires from each gage to a quarter-bridge circuit. The cavity resonant frequency is obtained from the minimum of the reflection coefficient measured with a vector network analyser (Agilent, E5071C).

Measurement Results

The pressure tank is filled with de-ionized water at room temperature and is pressurized with a hand pump. Strain and frequency are measured for each pressure value. Two sets of measurements were taken, one in which the pressure was released after each step and one in which the pressure was continuously increased, up to 6.12 atm, relative to atmospheric pressure. Frequency shift, Δf, and micro-strain ($\mu\varepsilon=10^{-6}\times\varepsilon$) as a function of relative pressure are shown in Figs. 3 and 4 respectively. Strain gage 1 could not be measured. The $\Delta f/\Delta P$ coefficient obtained from a linear fit of the frequency shift data is -65.7 kHz/atm.

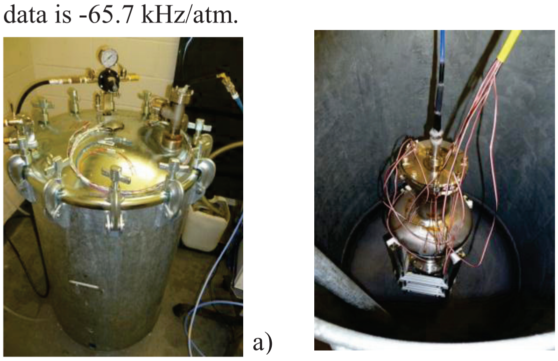

Figure 2: Pressure tank (a) with cavity set inside (b).

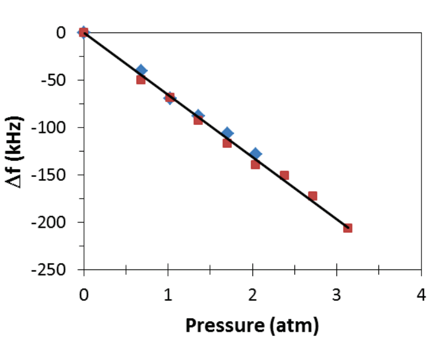

Figure 3: Frequency shift as a function of pressure, relative to 1 atm. The solid line is a linear fit to the data. Water began leaking into the RF connector above 3 atm.

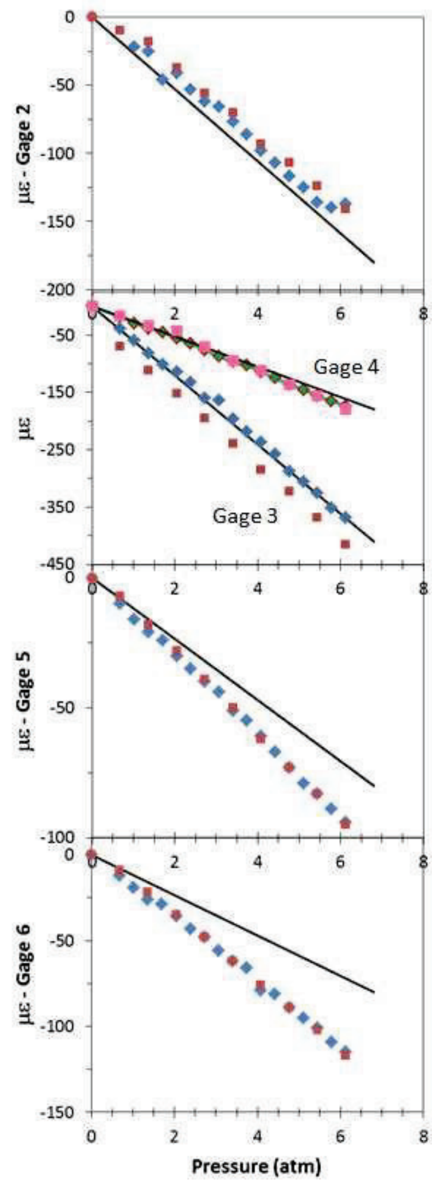

Figure 4: Micro-strain as a function of pressure, relative to 1 atm measured at different locations. Two set of measurements (square symbols and diamond symbols) are shown. Solid lines are obtained from FEM.

FINITE ELEMENT ANALYSIS

ANSYS version 14.5 was used to model the single cell cavity. A symmetry plane was defined at the equator location to minimize computation time. Roughly 14,000 triangular-shaped elements were utilized to mesh the cell. An elastic static structural model was considered and the niobium material properties were defined as isotropic.

Figure 5 shows the Von Mises stress and elastic strain along the y-axis for a 6.12 atm external pressure, respectively, obtained from the FEM using a Young's modulus value of E = 88.5 GPa and a Poisson's ratio ν = 0.2. The value of the Poisson's ratio was fitted to match the data for gages 3 and 4, which measured strain at the same location by along orthogonal directions.

ISBN 978-3-95450-132-8

ν-values of 0.27-0.397 are found in the literature [12-14]. The Von Mises stress at the gages' location obtained from FEM for an external pressure of 6.12 atm is: 36.5 MPa for gages 1-4, 12.5 MPa for gage 5 and 11 MPa for gage 6.

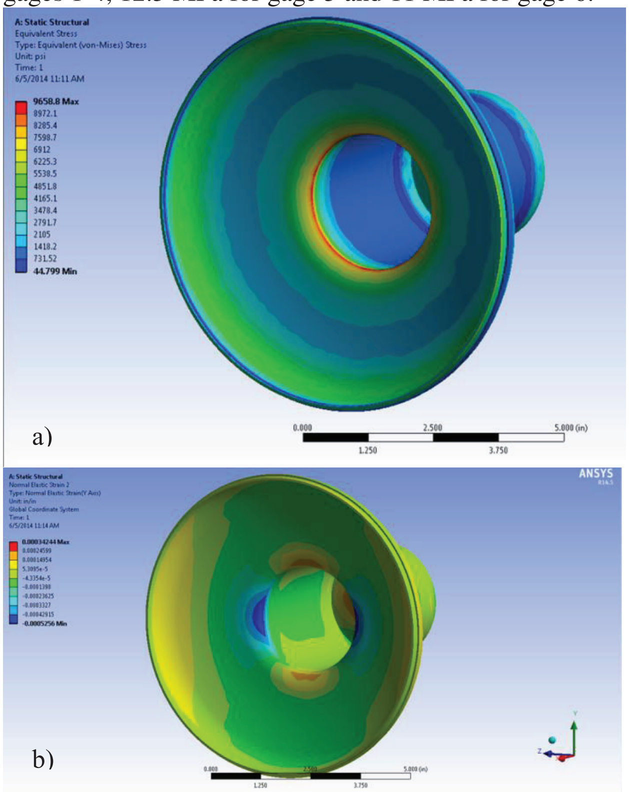

Figure 5: Von Mises stress (a) and strain in the y-direction (b) obtained by FEM for an external pressure of 6.12 atm.

DISCUSSION

The measurement of strain at different locations of an ingot Nb cavity subjected to external pressure showed the highest strain to occur near the iris region, in quantitative agreement with FEM simulations assuming E = 88.5 GPa and ν = 0.2. However, the data also indicate a significant strain in the equator region, higher than predicted by FEM. The cause for such discrepancy is not clear at the moment. One possibility is the assumption of isotropic material properties in FEM of the cavity. For example, the Young's modulus for Nb at room temperature ranges between ~88 GPa and ~150 GPa depending on the crystal orientation [7]. The anisotropic behaviour of the large (> ~1 cm) crystals of an ingot Nb cavity might have to be taken into account in the FEM to achieve better agreement with the experimental data.

The peak Von Mises stress at the iris (~66.5 MPa) obtained by FEM might be greater than the yield strength (~50 MPa) of the material for an external pressure of 6.12 atm. The Von Mises stress at the gages' location estimated by FEM at the highest pressure should be below the yield strength, in agreement with the data shown in Fig. 4. The highest pressure applied in this test is, in any case, much higher than during typical cool-down conditions of cavities in cryomodule.

CONCLUSION

Measurements and FE analysis of strain as a function of external pressure applied to ingot Nb cavities have been initiated at Jefferson Lab. Good agreement between the model and the data was found close to the iris region of a single-cell after fabrication. However, higher strain than predicted by FEM was measured close to the equator region.

Further measurements will be done on ingot Nb cavities after high-temperature (≥ 800 °C) heat treatments and on fine-grain cavities.

ACKNOWLEDGMENT

We would like to acknowledge S. Dutton of JLab for help with wiring of the strain gages; G. Cheng, S. Yang of JLab and T. Bieler of MSU for providing information about mechanical properties of Nb.

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