

STUDY OF AC/RF PROPERTIES OF SRF INGOT NIOBIUM

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Abstract

In an attempt to correlate the performance of superconducting radiofrequency cavities made of niobium with the superconducting properties, we present the results of the magnetization and ac susceptibility of the niobium used in the superconducting radiofrequency cavity fabrication. The samples were subjected to buffer chemical polishing (BCP) surface and high temperature heat treatments, typically applied to the cavities fabrications. The analysis of the results show the different surface and bulk ac conductivity for the samples subjected to BCP and heat treatment. Furthermore, the RF surface impedance is measured on the sample using a TE_{011} microwave cavity for a comparison to the low frequency measurements.

INTRODUCTION

Bulk niobium (Nb) has been the material of choice for the superconducting radiofrequency (SRF) cavities used in charged particle accelerators around the world. The fabrication of these complex three dimensional structures includes the deep drawing of the sheet Nb, electron beam welding, mechanical and chemical polishing, high temperature heat treatment and low temperature baking. These processes are commonly used to achieve high accelerating gradient and quality factor in SRF cavities. One of the issues towards achieving increasingly higher fields is the occurrence of a sharp increase of the radio frequency losses when the peak magnetic field, B_p , reaches about 90 mT, consequently limiting the operational accelerating gradient of SRF cavities [1]. This phenomenon is referred to as high field Q -slope or Q -drop. Besides the Q -drop, several factors are limiting the high gradient and quality factor, such as, field emission, multipacting, residual resistance and thermal instabilities.

The performance of the SRF cavities typically depends on the superconducting properties within the rf penetration depth (~ 40 nm). The bulk of the superconductor is also important for the mechanical and thermal stabilization of the SRF cavities. The superconductivity can persist in a thin surface layer of the type-II superconductor above the bulk upper critical field, H_{c2} . The thickness of this superconducting sheath is of the order of the coherence length (~ 40 nm for Nb) comparable to the microwave penetration depth. Thus, understanding the mechanism and properties of this superconducting sheath is important to understand the mechanism of the RF losses in SRF cavities. When the magnetic field is parallel to the cylindrical samples, the

surface superconducting sheath is of the form of a hollow cylinder and persistent current is induced on the surface during the increase in the external magnetic field. This screening current produces a hysteresis effect on the magnetization curve. In this contribution, we present the study of AC/DC and RF superconducting properties of the ingot niobium which was subjected to several chemical and heat treatments in an attempt to correlate the performance of SRF cavities.

EXPERIMENTAL SETUP

The dc magnetization of the samples was measured using the single coil magnetometer as described in Ref. [2]. The magnetization measurement were carried out on a cylindrical samples of length 120mm and diameter 12mm with concentric hole of 8 mm in the centre with one end closed. The samples were subjected to several chemical and heat treatment procedures. The details of experimental setup are described in Ref. [3]. The same sample was used to study the RF properties using the TE_{011} cavity [4].

AC susceptibility was measured using a home-made setup to the SQUID magnetometer as described in Ref. [5]. In-phase and out-of-phase components of the ac susceptibility at the fundamental frequency and the response at the second and third harmonics were measured using the pick-up coil method. A cylindrical Nb sample with diameter 2.9 mm and length 23 mm, cut out from ingot niobium was inserted into one coil of a balanced pair. The unbalanced signal as a function of the external parameters such as temperature, DC magnetic field, frequency, and amplitude of excitation was measured by a lock-in amplifier. The sample was cooled down in zero magnetic field and then a dc magnetic field was applied. The amplitude and phase of the unbalanced signal were measured. We assume that in a zero dc field at low temperatures and low amplitude of excitation the losses are negligible and the in-phase component of the ac susceptibility does not depend on frequency and equals $-1/4\pi$. This assumption permits us to get the values of χ' and χ'' in absolute units at other DC fields and temperatures. The DC magnetic fields H_0 , and AC field h_0 , were parallel to the cylindrical sample. The measurements were performed at $T = 4.5$ K.

RESULTS AND DISCUSSIONS

Magnetization

Figure 1 shows the result of magnetization measurements carried out at temperature 2K after several heat and surface treatments. The hysteresis (irreversible

magnetization) in the magnetization curve and several flux jumps were observed for all measurements. The first flux penetration as well as the upper critical field can be extracted from these measurements. The area of hysteresis after the high temperature heat treatment reduces due to the reduction of the interstitial impurities from the bulk. The upper critical field for the BCP treated sample is much higher (~ 0.5 mT), possibly due to the induced currents in the surface sheath contributing to the magnetic irreversibility by shielding the bulk of the superconductor in increasing and decreasing fields [6-8]. However, this is not observed after subsequent treatments, suggesting a reduction of the surface pinning centers after the first heat treatment. The field of first flux penetration and the upper critical field remain close for the sample treated with the low temperature baking and EP surface treatment.

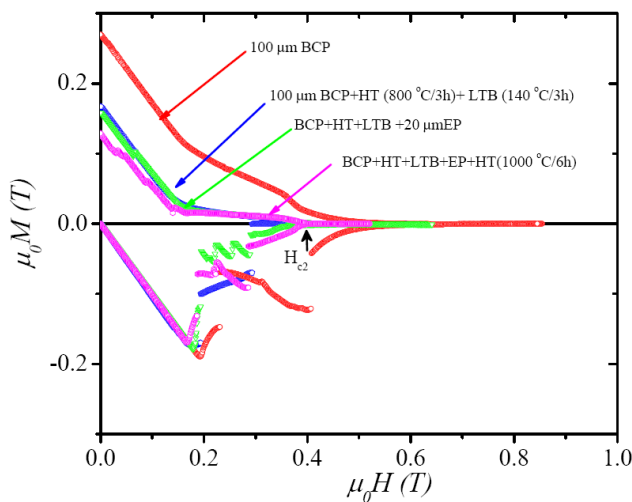


Fig. 1: The result of magnetization measurements carried out on an ingot niobium sample at 2 K which was subjected to several chemical and heat treatment typically applied to SRF cavities.

AC Measurements

Figure 2 shows the difference between measurement in point-by-point mode and in a swept field with $dH/dt = 20$ Oe/s of susceptibilities χ' and χ'' for samples LG1 and LG2. The sample LG1 was subjected to BCP surface polishing whereas, sample LG2 was heat treated at 600 °C for 10 hours in a UHV furnace after BCP. The sweeping of the DC field affects the AC response both in the mixed and surface superconducting states. The effect of a swept field is more noticeable at low frequencies. We found that in a swept mode there are some peculiarities of χ near H_{c1} and H_{c2} . These peculiarities provide evidence of the change in the underlying mechanism that is responsible for forming the AC response in the mixed and surface superconducting states. Above H_{c3} the susceptibility of the sample is defined by the normal conductivity.

Findings for $H_0 > H_{c3}$ allowed us to estimate the normal conductivity of the samples at 4.5 K. Thus for LG1 $\sigma = 8.0 \times 10^{18} \text{ s}^{-1}$ and for LG2 $\sigma = 1.3 \times 10^{19} \text{ s}^{-1}$. Experiment demonstrates that in point-by-point mode frequency dispersion and nonlinearity (third harmonics) appeared for $H_{c2} < H_0 < H_{c3}$. At the same time, in a swept field mode frequency dispersion and nonlinearity, including second harmonic signal, appeared for $H_0 > H_{c1}$ possibility of the vortex moving during a part of the ac period only. Such type of the behavior well coincides with our previous observation on single crystal niobium and thin film niobium [9, 10].

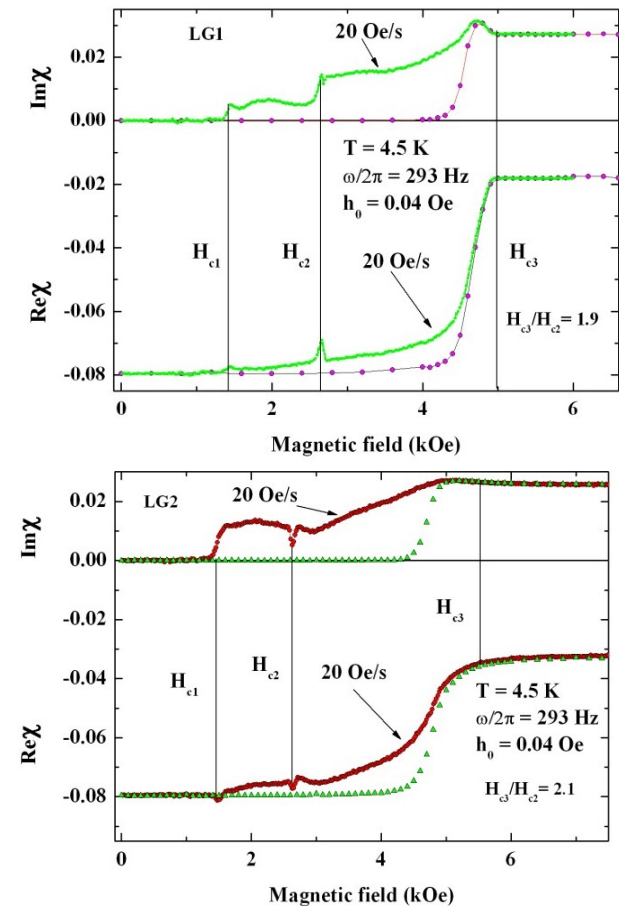


Fig. 2: Field dependence of χ' and χ'' in point-by-point mode and a swept field modes for LG1 (upper panel) and LG2 (lower panel) samples.

RF Measurements

Once the sample was measured for magnetization, the sample was inserted in a pill-box cavity forming a coaxial resonator [3]. The maximum surface magnetic field occurs in the middle of the sample the coaxial geometry, while it is in the middle of the cylinder in the case of the empty cavity. The ratio of the magnetic field on the sample surface to the cavity surface is 2.2. Furthermore, the total power dissipated on the sample over the total dissipated power in the cavity per unit resistance R_s is 30.4%. The cavity was tested without the sample and with

the sample inserted and the surface resistance of sample can be calculated as

$$R_{s,sample} = \left(\frac{P_{cavity+sample}}{P_{cavity}} - 1 \right) R_{s,cavity} 0.304$$

Figure 3 shows the surface resistance of the sample as a function of the peak magnetic field measured using the TE_{011} microwave cavity at 3.5 GHz. The maximum field was limited by the critical heat flux through the cooling channel in the center of the sample.

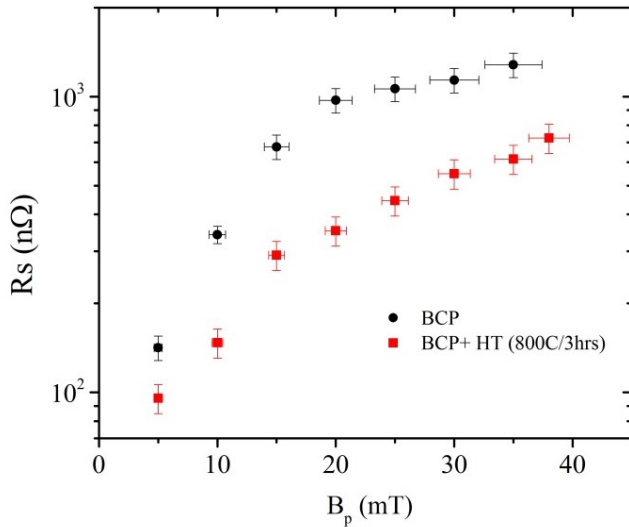


Fig. 3: Surface resistance as a function of the peak magnetic field measure at 3.58 GHz using the TE_{011} cavity for the sample subjected to BCP and HT.

SUMMARY

The magnetization, AC susceptibility and RF properties were measured for the sample subjected to BCP and heat treatments. The magnetization measurements showed the reduction of the hysteresis area after the heat treatment corresponding to the reduction of impurities (pinning centers from the bulk). The AC measurements showed increased normal state conductivity after the heat treatment as well as an increase in the ratio of critical field H_{c3}/H_{c2} after the heat treatment, most likely due to the reduction of the electronic mean free path in the surface of the sample [11]. It is found that in a swept DC field conductivity near the surface differs from the bulk one. The conductivity in mixed state depends on the excitation amplitude, frequency and sweep rate. As expected, the microwave surface resistance of the sample as function of field showed a reduction in surface resistance after the heat treatment. Since the highest peak magnetic field is limited by the critical heat flux through the cooling channel, a better cooling channel is planned. This TE_{011} cavity which will be capable of measuring the RF breakdown field for other alternative superconducting materials such as NbN, Nb₃Sn, and MgB₂.

Currently, there is no conclusive correlation to the RF performance to the sample studies since the measurement are done on two different set of samples but further

06 Material studies

F. Basic R&D bulk Nb - High performances

measurements of the DC magnetization and AC susceptibility are planned for the sample heat treated at higher temperature (~1600 °C) and will be compared these results of recent cavities performances [12].

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