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MAGNETIC FLUX EXPULSION IN SUPERCONDUCTING RADIO-FREQUENCY NIOBIUM CAVITIES MADE FROM COLD WORKED NIOBIUM*

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Abstract

Trapped residual magnetic field during the cooldown of superconducting radio frequency (SRF) cavities is one of the primary source of rf residual losses leading to lower quality factor. Historically, SRF cavities have been fabricated from high purity fine grain niobium with grain size 50 - 100 μm as well as large grain with grain size of the order of few centimeters. Non-uniform recrystallization of fine-grain Nb cavities after the post fabrication heat treatment leads to higher flux trapping during cooldown, hence the lower quality factor. We fabricated two 1.3 GHz single cell cavities from cold-worked niobium from different vendors and processed along with cavities made from SRF grade Nb. The flux expulsion and flux trapping sensitivity were measured after successive heat treatments in the range 800 – 1000 °C. The flux expulsion from cold-worked fine-grain Nb cavities improves after 800 °C/3 hours heat treatments and it becomes similar to that of standard fine-grain Nb cavities when the heat treatment temperature is higher than 900 °C.

INTRODUCTION

The performance of the SRF cavities is influenced by several intrinsic and extrinsic parameters. One of the significant contributing factor being the trapped mangetic flux due to the insufficient flux expulsion of ambient magnetic field from the SRF cavities when cavities cool-down through the superconducting transition temperature [1–4] . In theory, during the superconducting phase transition, all residual magnetic flux should be expelled from the bulk of the superconductor. However, material defects, dislocations, segregation of impurities provide favorable sites for magnetic flux pinning, which contribute to an additional rf loss when exposed to the rf field. It has been demonstrated that several different pinning mechanism plays a role to the rf losses due to vortices [4]. Studies showed that doped cavities are more vulnerable to the vortex dissipation loss due to the presence of the dopant on cavities rf surface [3, 5, 6].

Earlier studies on flux expulsion and rf losses due to pinned vortices showed that the better flux expulsion can be achieved when the cavity annealing temperature is increased [7]. The increase in annealing temperature minimizes the pinning centers by removing the clusters of dislocations and impurities. In addition, the metallurgical state with larger grain size is expected as the annealing temperature is increased. Fine-grain recrystallized microstructure with an average grain size of 10 - 50 μm leads to flux trapping even with a lack of dislocation structures in grain interiors [8]. Here, we have conducted a systematic study on cold work SRF niobium in an attempt to correlate the metallurgical state with respect to the flux expulsion, flux pinning and flux trapping sensitivity. One of each 1.3 GHz TESLA shape single cell cavities were fabricated from cold work sheet from two different vendors as well as the standard cavity grade SRF niobium. The cavities were fabricated and processed together along with witness samples to analyze the metallurgical state as well as pinning strength with respect to the process applied to cavities.

CAVITY FABRICATION AND SURFACE PREPARATIONS

Fine grain Nb sheet of thickness ~3 mm SRF grade high purity with residual resistivity ratio greater than 350 were purchased from two different Nb vendors. In addition, a special order was made with vendors to provide the cold work with no post processing at vendor site. The vendors did not provide any material specifications for cold work sheets, however the sheets were made out of the same batch of SRF grade niobium and the final recrystallization step was omitted. The electron backscattered diffraction–orientation image (EBSD-OI) on two sets of Nb sheet along with the two single cell cavities fabricated at Jefferson Lab are shown in Fig. 1 from material provided by Tokyo Denkai. The second set of cavities were fabricated at cavity manufacturer from the material provided by Ningxia. The fabrication of cavities were followed the standard practice of deep drawing to half cells, trimming, machining of the iris and equator of the half-cells, electron beam welding of the beam tubes (made from low purity niobium).

After the cavity fabrication, the cavities were chemically polished by electropolishing (EP) in a horizontal, rotating setup, using a mixture of electronic grade $HF{:}H_2SO_4$ = 1:9 at a constant voltage of ~14 V, temperature of 15 - 20 °C and a speed of 1 rpm. The total bulk removal of ~150 μm at cavity equator was removed by EP. The first cycle of heat treatment of the cavity was done at 800 °C for 3 hours in UHV furnace.

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Figure 1: 1.3 GHz TESLA shaped single cell cavities fabricated with SRF grade Nb (left) and cold work Nb (right). Also shown is the cross-sectional EBSD-OI for respective sheet materials.

The cavity was again subjected to EP at temperature lower than 5 °C. The successive heat treatment of 900 and 1000 °C for 3 hours followed by 25 µm EP was done before each cavity test.

EXPERIMENTAL SETUP

Three single-axis cryogenic flux-gate magnetometers (FGM) (Mag-F, Bartington) were mounted ~ 120°, apart on the external cavity surface parallel to the cavity axis in order to measure the residual magnetic flux density during the cooldown process. 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 flux-gate magnetometers. The distance between the temperature sensors at top and bottom irises is ~ 20 cm. The measurement protocols consisted of two parts. The first part involved several cooldown and warm up cycles above 10 K in order to explore the flux expulsion ratio while changing the temperature gradient along the cavity axis. The second part of the measurement procedure was as follows: (i) the magnetic field was initially set below 1 mG using the field compensation coil that surrounds the vertical dewar. (ii) The cavity cool-down process was applied, resulting in < 0.1 K temperature difference between the top and bottom iris. The temperature and magnetic field were recorded until the dewar was full with liquid He and a uniform temperature of 4.3 K was achieved. This step assumes that all applied magnetic field is trapped into the SRF cavity. (iii) $Q_0(T)$ at low rf field (peak surface rf magnetic field B_p ~ 20 mT) from 4.3 – 1.6 K was measured using the standard phase-lock technique. (iv) Q_0 vs E_{acc} was measured at 2.0 K. (v) The cavity was warmed up above T_c and the residual magnetic field in Dewar is set to certain values (~20 and ~40 mG). Steps (ii) to (iv) were repeated for different values of magnetic field.

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 complete trapping of magnetic field during cooldown, whereas a flux expulsion ratio of ~1.7 at the equator would result from the ideal superconducting state. A representative plot of the residual magnetic field at the FGMs locations measured during one cool-down cycle for cavity is shown in Fig. 2. The average value of B_{sc}/B_n for the three FGMs at the equator was 1.55 ± 0.03. The temperature difference between the top and bottom iris when the equator of the cavity reached transition temperature ~9.3 K is 3.28 K.

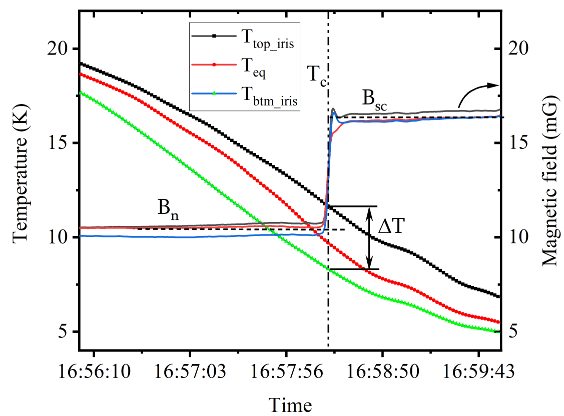

Figure 2: Temperature and magnetic field during transition from normal to superconducting state measured during a cool-down cycle.

Figure 3 shows the results of flux expulsion measurements on 4 cavities under this study after 800 °C/3 hours heat treatment and successive heat treatment at 1000 °C/3 hours. Not shown here, the cavity was also heat treated at 900 °C/3 hours and measurements were repeated before additional 3 hours heat treatment at 1000 °C. It is clearly seen that cavities fabricated with SRF grade Nb showed the poorer flux expulsion after 800 °C/3hours heat treatment compared to cavities made from cold work Nb. The flux expulsion ratio showed similar behavior after successive heat treatment at 1000 °C/3 hours.

RF Measurements

The average rf surface resistance was obtained from the measurement of $Q_0(T)$ at low rf field (B_p ~ 20 mT) for different applied dc magnetic field, B_a, prior to each cool-down. The $R_s(T)$ data were fitted with the generic expression and method used in Ref. [9] to extract the residual resistance. The residual resistance as a function of trapped residual magnetic field was fitted to extract the flux trapping sensitivity, the increase in residual resistance per mG of trapped residual

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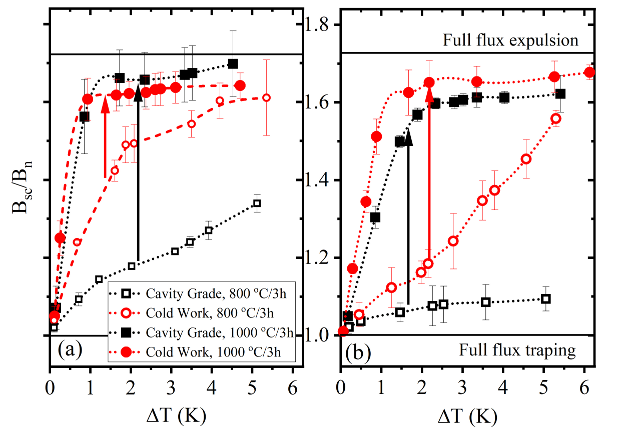

Figure 3: The flux expulsion ratio B_{sc}/B_n as a function of temperature difference $\Delta T = (T_{\text{top-iris}} - T_{\text{bottom-iris}})$ for cavities made from traditional and cold work Nb sheet from vendors (a) Ningxia and (b) Tokyo Denkai.

magnetic field. The flux trapping sensitivity was ~ 0.35 - 0.45 nΩ/mG for all cavities when final surface preparation was electropolishing. When the final surface preparation was changed to low temperature baking at 120 °C, the flux trapping sensitivity increased as high as 0.67 nΩ/mG depending on the duration of bake [10]. In literature, the flux trapping sensitivities were as high as a few nΩ/mG for nitrogen doped cavities [4, 5].

SUMMARY AND FUTURE OUTLOOK

As shown in Fig. 3, the flux expulsion for cavity made from cold work Nb showed a better expulsion when the cavity was heat treated at 800 °C/3 hours compared to SRF grade Nb. After a 900 °C and 1000 °C heat treatment, the initial microstructure state of the cavity sheet no longer affects the flux expulsion performance. On the other hand, the flux trapping sensitivity depends on the final surface preparation of the cavities before the rf test. The poor flux expulsion will result in higher flux sensitivity if the final surface preparation is other than electropolishing. When the rf surface is modified with impurity doping, the flux trapping sensitivity increases. Thus, efficient flux expulsion is required to minimize the additional rf loss related to the trapped flux. It is possible to achieve the full flux expulsion limit on cavities fabricated with cold work Nb after 800 °C/3 hours heat treatment if one can maintain the temperature gradient between the cavities irises above 5.0 K, which is not the case with cavities made from SRF grade Nb. To achieve the high flux expulsion ratio and hence the high quality factor in nitrogen doped SRF cavities, some of the cavities used in LCLS-II project were heat treated as high as 975 °C. Achieving good flux expulsion at lower annealing temperature has an advantage of keeping a higher yield strength and better mechanical stability of Nb cavities.

Several sample coupons from half-cell cut out and sheets were also processed along with the cavities in order the understand the metallurgical state and superconducting pinning properties with respect to heat treatment temperature. There is a correlation of flux expulsion ratio with the grain size, recrystallization and reduced pinning force as a result of high temperature heat treatment. The more detailed sample coupon studies and comparison with cavity performance will be presented in future publications. Additionally, the rf surface modifications to understand the flux trapping sensitivity with impurity doping and oxygen alloying on cavities made from SRF grade and cold work Nb is left for future study.

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