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EFFECT OF DURATION OF 120 °C BAKING ON THE PERFORMANCE OF SUPERCONDUCTING RADIO FREQUENCY NIOBIUM CAVITIES*

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Abstract

Over the last decade much attention was given in increasing the quality factor of superconducting radio frequency cavities by impurity doping. Prior to the era of doping, the final cavity processing technique to achieve the high accelerating gradient includes the “in-situ” low temperature baking of SRF cavities at temperature ~ 120 °C for several hours. Here, we present the results of a series of measurements on 1.3 GHz TESLA shape single-cell cavities with successive low temperature baking at 120 °C up to 96 hours. The experimental data were analyzed with available theory of superconductivity to elucidate the effect of the duration of low temperature baking on the superconducting properties of cavity materials as well as the rf performance. In addition, the rf loss related to the trapping of residual magnetic field refereed as flux trapping sensitivity was measured with respect to the duration of 120 °C bake.

INTRODUCTION

The performance of superconducting radio frequency (SRF) cavities are measured in terms of quality factor as a function of accelerating gradient. Higher quality factor with high accelerating gradient are desirable for operation of high energy future particle accelerators. Over the last decades, high quality factor at medium accelerating gradient (20 - 25 MV/m) was achieved by impurity doping with Ti or N [1–3]. The effect of low temperature baking in the presence of nitrogen also resulted increase in quality factor at medium accelerating gradient and it was extended to higher accelerating gradient over the baseline measurement [4, 5]. Most recently, the medium temperature heat treatment also resulted in the increase in quality factor likely due to the decomposition of surface oxide phase and oxygen diffusion within the rf penetration depth [6, 7].

The role of the low temperature baking (120 - 150 °C) on the performance of SRF cavities was studied extensively, mainly eliminating the high field Q-slope and few models were proposed in the past [8–12]. The oxygen diffusion model proposed by G. Ciovati [13], qualitatively explains the diffusion of oxygen in to the rf surface of SRF cavities. The same model also describes well to the diffusion of oxygen during the mid-T heat treatment (300 - 400 °C) [7]. Here, we present a systematic study on the performance of SRF cavities subjected to the low temperature baking to understand the effect of 120 °C baking duration. We extract the superconducting parameter from the temperature dependence of surface resistance and penetration depth.

CAVITY SURFACE PREPARATION AND RF MEASUREMENTS

Two TESLA-shaped 1.3 GHz single cell cavities (G = 277.85, B_p/E_{acc} = 4.23 mT/(MV/m)) were fabricated from high purity Nb. One of the single cells labeled TE1-05 was fabricated from fine-grain ASTM 5 Nb with RRR ~ 400 and second cavity labeled TE1-06 was fabricated from a cold work niobium sheet. The cavities were processed with several heat treatment cycles in the range of 800 - 1000 °C followed by ~ 25 µm electropolishing as the final surface preparation. The cavities were subjected to high pressure rinse, dried in clean room overnight and assembled with probes and pump-out port.

The cavities were loaded in the vertical Dewar to measure the flux expulsion when the cavity transitions to the superconducting state during cooldown. The details of flux expulsion technique are given in Refs. [14, 15]. Both cavities showed excellent flux expulsion when the temperature gradient across the irises is kept > 2.0 K. The baseline rf measurements were done with cavity cooldown in minimum residual magnetic field (< 1 mG) in Dewar with high temperature gradient ($\Delta T > 4K$) across the cavity irises to ensure good flux expulsion of any residual magnetic field. The Q_0 vs. the helium bath temperature (T) measurement was done from 4.3 to 1.6 K at B_p ~ 15 mT. A representative plot for $R_s(T)$ is shown in Fig.1 for cavity TE1-06 after electropolishing followed by 120 °C bake for 3 hours. At 2.0 K, the Q_0 vs. E$_{acc}$ measurement was carried out. The second set of measurements was done after warming the cavity above T$_c$ and cooldown with ~20 mG residual magnetic field in Dewar. The cavity was cooled with temperature gradient across the cavity < 0.1 K (B_{sc}/B_{nc} ~ 1), ensuring that maximum ambient magnetic field was trapped during the cooldown. Again, the Q_0 vs. T measurement was repeated from 4.3 to 1.6 K and at 2.0 K, the Q_0 vs. E$_{acc}$ measurement was done. This allows us to extract the flux trapping sensitivity, the increase in surface resistance due to the trapped residual magnetic field during cooldown.

The cavities were subjected to low temperature baking at 120 °C for several hours in the interval of (3, 6, 12, 24, and 48 hours) in a bake box. During the cavity baking process, the cavity was kept under vacuum (< 10^{-7} torr). The rf measurements of Q_0 vs. T and Q_0 vs. E_{acc} were repeated

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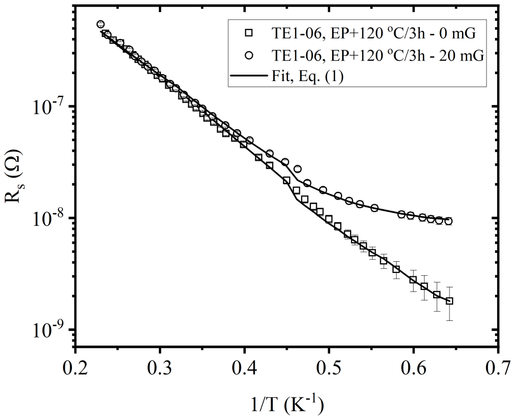

Figure 1: R_s vs. 1/T for cavity TE1-06 after electropolishing followed by 120 °C/3hrs baking with < 1 mG and ~ 20 mG trapped flux.

with different residual field trapped during the cooldown. The R_s (G/Q_0) vs. (1/T) data were fitted as described in Ref. [16] using the following equation:

$$R_s(T) = Ae^{-U/T_s} + R_i \tag{1}$$

where R_i refers to residual resistance due to the several intrinsic and extrinsic contributions such as trapped magnetic field during cooldown, non superconducting nano-precipitates, sub-oxide layer at the surface, broadening of the density of states, etc. The first term Ae^{-U/T_s} is due to the thermally activated quasi-particles in rf field. For weak rf field, the term is a good approximation of the Mattis-Bardeen expression for R_{BCS}, where U represents the superconducting gap [17], T_s is the temperature of cavity's rf surface. A summary of the $R_s(T)$ fits for cavities cooldown with < 1 mG is shown in Fig. 2. The fits were also repeated for cavities with ~ 20 mG trapped residual field with no significant change in A and U, however the residual resistance R_i increases. The flux trapping sensitivity $S(n\Omega/mG)$ was calculated as:

$$S = \frac{R_{i,20mG} - R_{i,0mG}}{20} \tag{2}$$

Figure 3 shows the flux trapping sensitivity for two different cavities after successive 120 °C baking. Figure 4 shows the Q_0 vs. E_{acc} for cavities after electropolishing and additional 120 °C baking for 3 hours. The electropolished cavities were limited by high field Q-slope. Surprisingly, the high field Q-slope was eliminated just after 3 hours baking at 120 °C. Similar improvement was observed in large grain cavities treated with buffered chemical polishing followed by 120 °C in-situ baking for 3 hours [18]. While increasing the baking time to as high as 96 hours, no significant change in quenched gradient was observed.

In order to obtain information about the mean free path near the surface, we measured the resonant frequency and quality factor while warming up the cavities from ~ 4.3 K to higher than transition temperature (> 9.3 K) using vector-network analyzer, from which $R_s(T)$ and the change in resonant frequency was extracted. The frequency shift can be translated into a change in penetration depth according to

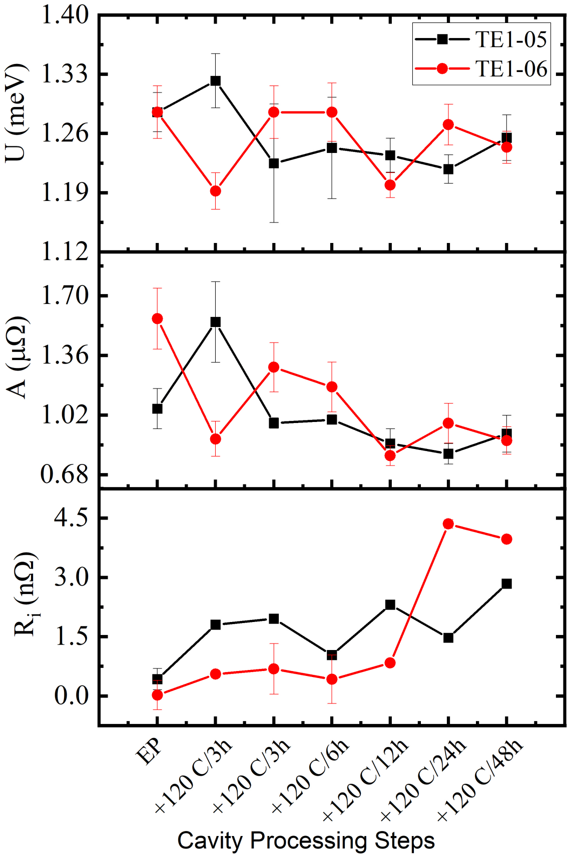

Figure 2: The summary of result of $R_s(T)$ for cavities with < 1 mG flux trapping during the cavity cooldown.

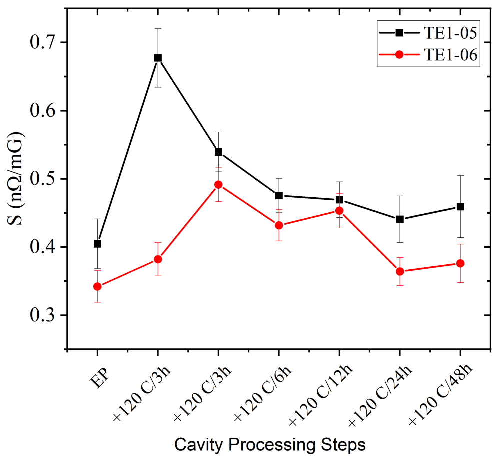

Figure 3: The flux trapping sensitivity as a function of different cavity processing steps.

$$\Delta\lambda = \frac{G}{\pi\mu_0 f^2}\Delta f \tag{3}$$

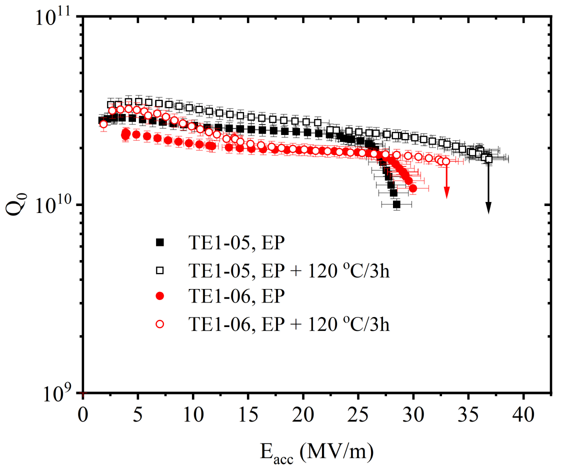

Figure 4: The Q_0 vs. E_{acc} at 2.0 K for electropolished and 120 °C/3hrs baked cavities. The vertical arrow represent that the cavities performance is limited by quench.

with G being the geometric factor of the cavity, f is the resonant frequency. The data in the superconducting state were fitted using the numerical solution of M-B theory. The mean free path decreases with the increase in 120 °C baking time. A more detailed analysis of the temperature dependence of penetration depth will be presented in a future publication.

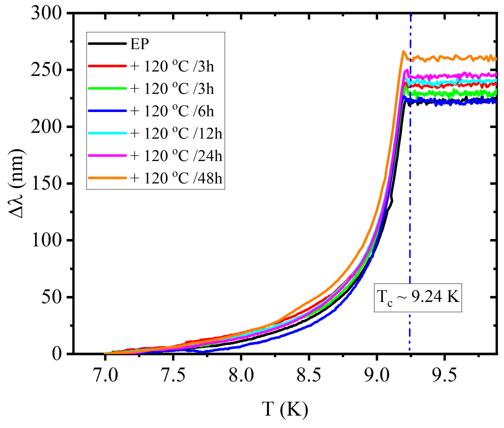

Figure 5: The change in penetration depth as a function of temperature during the superconducting to normal transition during cavity warm up.

SUMMARY

The effect of 120 °C baking was investigated with increasing the baking time. The residual resistance was extracted from the fit of generic temperature dependence (Eq. (1)) taking into account of the rf heating on the inner cavity surface [16]. As a result of 120 °C baking, the residual resistance R_i shows a small increase when cavities were cooled with little or no trapped residual magnetic field. However, when the cumulative baking time is higher than 48 hours, the increase in residual resistance is more apparent as shown in Fig. 2. The results are consistent with those reported in literature [9]. The increase in residual resistance was observed along with the decrease in temperature dependent (R_{BCS}) mainly due to the reduction in electronic mean free path.

Interestingly, the flux trapping sensitivity measurements showed the lowest sensitivity when the final surface preparations is electropolishing. Both cavities showed ~ 0.3 - 0.4 nΩ/mG for electropolished cavities. The sensitivity jumps much higher for cavity TE1-05 after 3 hours of baking, and gradually drops. The increase in flux trapping sensitivity peaked for cavity TE1-06 after 6 hours of baking. The flux sensitivity remains close for longer baking time. The calculations based on the oxygen diffusion models described in Refs. [7, 13] predicts the dilute oxygen concentration on the rf surface and oxygen diffuse deeper into the bulk. Even though, the final surface preparation may play some role on the initial condition of rf surface and successive baking duration, the cavity TE1-05 showed higher flux trapping sensitivity compared to cavity TE1-06. Furthermore, the cavity TE1-06 was fabricated from cold worked Nb, may have less density of dislocations and better recrystallization compared to TE1-05 cavity, leading to lower flux trapping sensitivity [14, 19]. The Q_0 vs. E_{acc} measurements at 2.0 K showed that the high-field Q-slope is eliminated just after 3 hours of baking at 120 °C.

As shown in Fig. 5, the superconducting transition temperature didn't change due to the duration of 120 °C bake. The increase in penetration depth in normal state (above 9.24 K) is the indicative of dirtier rf surface, likely due to dissolution of surface oxides. In addition, small enhancement in penetration depth close to T_c was observed. A much pronounced peak was reported in nitrogen and titanium doped cavities [20]. More systematic studies with different surface modification with higher temperature baking (200-400 °C) are planned in order to understand the effect of baking on performance of SRF cavities and flux trapping sensitivity.

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