TEMPERATURE EXCURSIONS IN Nb SHEETS WITH IMBEDDED DELAMINATION CRACKS

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Abstract

Delamination cracks can form in rolled Nb sheets, and between layers with different micro-structures. Such cracks cause resistance to heat conduction from the RF surface to the liquid He bath. A delamination crack can negate the advances in manufacturing processes that have enhanced the thermal conductivity of Nb. Here, temperature excesses are calculated as functions of crack size and location, and the power dissipated at an imperfection in the RF surface. A disk shape of Nb sheet is modeled as having adiabatic sides. A hemispherical defect is located on the RF surface at the center of this section. A crack is modeled as a void within the Nb disk. The Kapitza resistance between the Nb surface and liquid He is varied. The results indicate that an incipient crack leads to a decrease in the magnetic flux required to cause thermal breakdown. The decrease in the field is gradual with increasing crack radius, until the crack radius nearly equals the section radius, after which the field required for breakdown decreases sharply. To a lesser extent, the field strength for thermal breakdown also decreases with increased crack depth.

INTRODUCTION

Maintaining super-conducting state is crucial for SRF applications. Thermal breakdown of a superconducting radio frequency (SRF) cavity occurs when the rf surface temperature reaches its critical temperature [1]. Recent progresses in Nb cavities for particle accelerators has resulted in significant increase in thermal breakdown field up to 180~200 mT, which is close to the thermodynamic critical field (200 mT) [2, 3]. However, imperfections such as defects or dislocations can cause to a sharp decrease of thermal breakdown field [4]. Delamination cracks might also be a factor to decrease the field because of its resistance to heat conduction between the rf surface and liquid He bath. Recent studies at FRIB of MSU [5] shows that after EB spot welding, a crack in the 2 mm Nb sheet of the outer conductor was discovered. The crack is approximately in the middle of the sheet, splitting the sheet in two parts and propagating around 25 mm along the circumference, the depth of crack cannot be determined. Fig.1 and Fig. 2 are the picture and microscopic image of the delaminating crack, respectively. It is essential to study the influence of crack on thermal breakdown field and surface temperature of Nb.

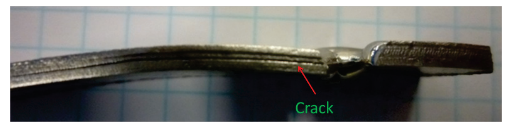

Figure 1: Picture of the delamination crack.

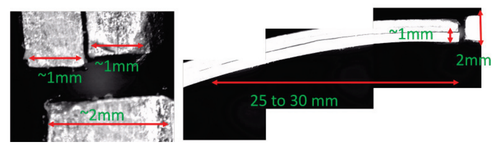

Figure 2: Microscopic image of the delamination crack.

MODELING

While a one dimensional thermal resistance network model might be used, a two dimensional transient heat transfer problem considering edge effects, crack effects, and temperature dependent thermal conductivity coupled with surface-surface radiation is modeled using multi-physics COMSOL. Fig.3 shows the geometry of the model, where r_c and r_{Nb} are the radius of the crack and Nb, respectively. h is the crack thickness and r_d is the radius of the defect. A finite cylindrical Nb disk with thickness d and radius r bounded by liquid helium on the lower surface and by a uniform rf magnetic field H on the top surface is modeled.

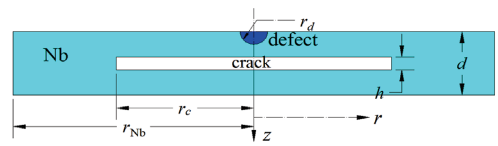

Figure 3: Geometry of the heat transfer model.

The governing equation of this model can be written as:

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial z^2} = \frac{1}{\alpha(T)}\frac{\partial T}{\partial t} \quad (1)$$

where $\alpha(T)$ is the thermal diffusivity of Nb and is defined as $\alpha(T) = k(T)/(\rho C)$, $k(T)$ is the temperature dependent thermal conductivity, shown in Fig. 4. C is the heat capacity and ρ is the mass density.

Initial and Boundary Conditions

Initial temperature of Nb can be set to any temperature below 9.25 K (critical temperature of Nb), here T_0 is chosen to be the liquid He temperature (1.6 K). T_0 is the temperature when time is 0.

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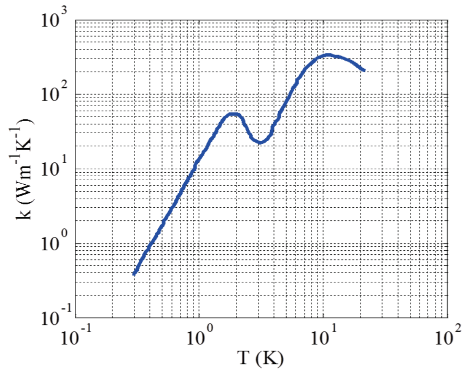

Figure 4: Temperature dependent thermal conductivity.

At the top surface where the defect is located, the power dissipated at the surface is expressed as:

$$q_d = \frac{1}{2} H^2 R_d A_d \tag{2}$$

The power dissipated by the BCS surface is defined as:

$$q_{BCS} = \frac{1}{2} H^2 R_d A_d \tag{3}$$

where R_d and R_{BCS} are the defect resistance (R_d) and BCS surface resistance(R_{BCS}) [4], respectively. R_d is 4 orders of magnitude greater than R_{BCS}. H is the magnetic field with units A/m, A_d and A_{BCS} are the surface area of the defect and Nb surfaces, respectively. A convenient analytical expression for the BCS surface resistance is [4]:

$$R_{BCS}(T) = 1.61 * 10^{-4} f_n^2 \frac{1}{T} ln(\frac{16T}{fn}) exp[-17.2 \frac{g(T)}{T}] \tag{4}$$

where $f_n = f(GHz)/2.856$, f is the microwave frequency in GHz, $g(T) = \Delta(T)/\Delta(0)$ is the reduced gap function and is approximated as [6]:

$$g(T) = [cos(\pi t^2/2)] \tag{5}$$

where $t = T/9.25$ is the reduced temperature. It is assumed that the rf critical field is the thermodynamic field (B=200 mT). The BCS surface resistance will be increased to a normal state value of 8*10^{-3} Ω.

At the lower surface of the Nb disk which is in contact with liquid He, the boundary condition is assumed to be heat flux from the outer Nb surface to the He bath for a temperature difference ΔT with Kapitza resistance.

$$k \frac{\partial T}{\partial z}(r, z) = Q(\Delta T) = \frac{\Delta T}{R_K} \tag{6}$$

where R_K is the Kapitza resistance for annealed Nb sample [8]. R_K = 0 when a constant temperature boundary $T(r, d)$=1.6 K is chosen.

In addition, it is assumed to be vacuum inside the crack and surface to surface radiation is considered as the boudady conditions for the crack. A hemisphere defect with radius to be 0.2 mm is considered in the model (large defects), the size of the defect is also varied to study its influence on thermal breakdown field.

RESULTS AND DISCUSSION

Temperature Profile with Respect to Cracks

Fig. 5 and Fig. 6 shows the steady state volume temperature profile without crack and with crack ($r_c = 0.7 r_{Nb}$) after 10 seconds, in fact the temperature will become steady after less then 1 second when the crack radius is less than 90 % of Nb disk. The thermal breakdown field for no crack is calculated to be 21.58 mT when the highest surface temperature reaches the critical temperature of Nb (T_c =9.25 K). Using the same magnetic field, the highest temperature calculated when $r_c = 0.7 r_{Nb}$ is 10.2 K, almost a degree higher, and the thermal breakdown field calculated for such a crack is 18.77 mT. The difference between our results with defect (r_d =0.2 mm) and no crack (B_b = 21.58 mT) and reference [4] is that we used annealed un-deformed single crystal Nb with RRR=250 [7], shown in Fig. 4. The thermal conductivity value is between 10 Wm^{-1}K^{-1} and and 200 Wm^{-1}K^{-1} for T between 1 K and 9 K, reference [4] used un-annealed Nb thermal conductivity data from CERN, the highest value is less than 6 Wm^{-1}K^{-1}. Thermal conductivity has played a very important role in determining the thermal breakdown field and it is studied later in this paper.

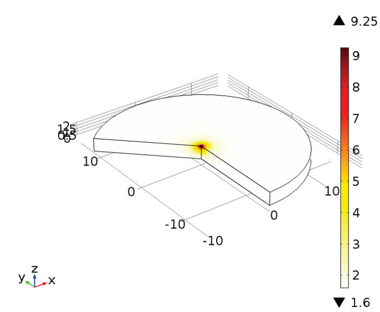

Figure 5: Steady Temperature profile (after 10 seconds) without crack with B=21.58 mT.

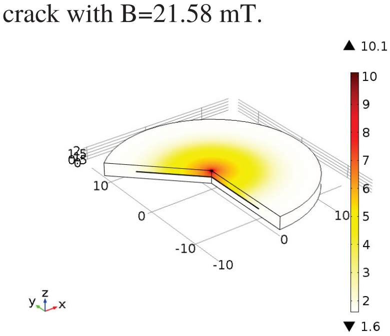

Figure 6: Steady Temperature profile (after 10 seconds) with crack with B=21.58 mT.

Crack Spanning the Nb Sheet

Given sufficient time, thermal breakdown will always happen if the crack spans the Nb sheet, no matter how small the defect is (or even no defect) and how less power applied to the cavity. The reason is that as the operating temperature is very low, the radiation heat transfer rate is much smaller than the heat conduction rate. If the radius of crack is smaller

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than Nb, there is always heat conduction through Nb between upper bound and lower bound of the crack. When their radius is the same, there is no heat conduction through the crack, heat will be trapped at the upper bound, causing temperature to increase rapidly, leading thermal breakdown. Fig. 7 is the temperature profile when the crack spans the Nb sheet, it clearly shows the heat sink at the upper bound.

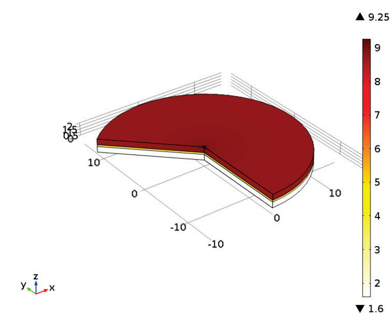

Figure 7: Temperature profile when crack is spanning the Nb sheet.

As thermal breakdown will always happen when the crack is taking up the entire Nb sheet, it is necessary to calculate the time required for thermal breakdown, and it is shown in Fig. 8. It would be a dangerous problem in this situation, as the highest breakdown field in several seconds is less than 10 mT with a defect, much lower that the usual operating magnetic field (20 to 30 mT). Measures has to be taken to avoid such case to happen.

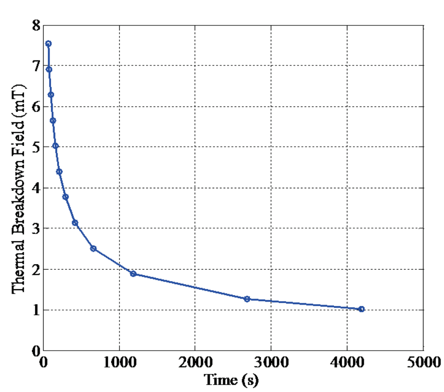

Figure 8: Thermal breakdown field related with time.

Effect of Crack Size on Thermal Breakdown Field

The thickness and radius of Nb in this model is assumed to be 2.1 mm and 15 mm, respectively. As it is shown in Fig. 9, thermal breakdown field decreases rapidly when there is a crack inside the Nb sheet, as the crack size increases, thermal breakdown field decreases more and more slowly, until reaching a certain point, after that the field will decrease sharply. Here, the certain point changes with the defect size and the size of Nb sheet, for r_{Nb}=15 mm, d=2.1 mm, h=0.1 mm, and r_d=0.2 mm, the crack radius is calculated to be 96% of Nb radius to reach the certain point. The breakdown field also decreases with increased crack thickness (h), but with smaller influences.

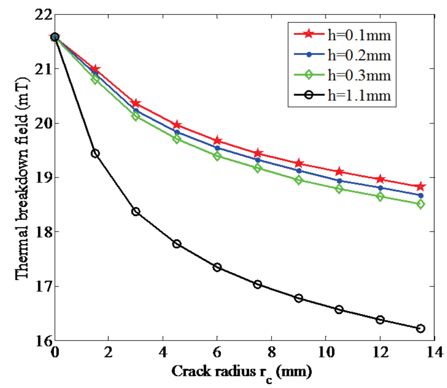

Figure 9: Influence of crack size on thermal breakdown field.

Effect of Defect Size and Thermal Conductivity on Thermal Breakdown Field

Using the same size as the last section for Nb, crack radius and thickness is chosen to be 10 mm and 0.1 mm, respectively. By varying the defect size and thermal conductivity data (constant value or temperature dependent), thermal breakdown field with or without crack is calculated and plotted, shown in Fig. 10. The breakdown field decreases rapidly when a defect is introduced on the top surface, then it decreases slowly with increasing defect size. Thermal conductivity (k) of Nb has played a significant role in determining the thermal breakdown filed. It can be seen from the figure that if k is chosen to be a constant (30 Wm^{-1}K^{-1} or 50 Wm^{-1}K^{-1}), even without crack, the breakdown field is much smaller than that using annealed temperature dependent thermal conductivity data [7] with crack inside.

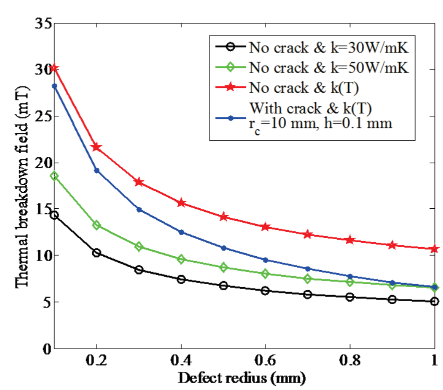

Figure 10: Influence of defect size and thermal conductivity on thermal breakdown field.

Effect of Crack Location on Breakdown Field

Thermal breakdown field also depends on the location of the crack. Three cases (crack in the lower bound, middle and upper bound of Nb sheet) were investigated to plot the

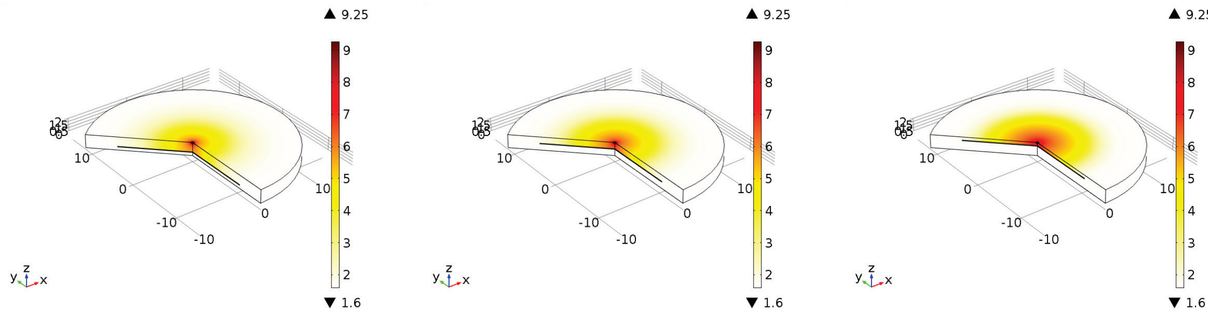

Figure 11: Temperature profiles when thermal breakdown occurs with different crack locations, (left): B_b =20.05 mT for crack at 1.5 mm from SRF surface, (middle): B_b =19.10 mT for crack at 1mm, (right): B_b =16.59 mT for crack at 0.5 mm, B_b is the breakdown field.

temperature profile when the thermal breakdown occurs, as shown in Fig.11. Thermal breakdown field calculated for those three cases are 20.05 mT, 19.10 mT, and 16.59 mT, respectively. There is more heat sink when the crack is closer to the BCS surface.

CONCLUSIONS

Delamination cracks can form during manufacturing processes. A parametric study using multi-physics Comsol is carried out to investigate their influence on thermal breakdown field, which is crucial to SRF performance. Surface temperature increases when a crack is introduced, and it increases rapidly as the crack takes up the entire Nb sheet, at which case thermal breakdown will always occur. When the crack spans the Nb disk, the time required for thermal breakdown depends on the field applied to the surface, from several seconds when the field is relatively strong (B~8 mT) with defect to several thousand seconds with weak field (B~1 mT) with no defect. Thermal breakdown decreases with the increase of crack size (radius, thickness), effect of radius is more significant than thickness. The field decreases rapidly when the crack radius is close to the Nb radius, in the case studied here, the ratio (r_c/r_{Nb}) is 96%. Thermal breakdown field will also decrease with increasing defect size and it decreases rapidly when a defect is introduced. The value of thermal conductivity is crucial in determining the thermal breakdown field. High values of thermal conductivity will help to diminish the effect of the crack. Therefore, cracks should be avoided during manufacturing processes, or at least large cracks should be avoided and far from the SRF surface. Efforts should be made to decrease imperfections and to increase the thermal conductivity of Nb.

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