THERMAL DESIGN STUDIES OF NIOBIUM SRF CAVITIES*

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Abstract

The thermal response of niobium cavities at liquid helium temperatures remains an active area of research in order to increase the accelerating gradients of future accelerators. The effects of plastic deformation on the thermal conductivity in the phonon transmission regime, as well as on the Kapitza conductance, have been studied. The study reveals absence of the phonon peak after deformation beyond the elastic limit of niobium, with an almost 80% reduction in the thermal conductivity of niobium at 2 K. Deformation also reduced the Kapitza conductance. Low temperature annealing did not recover the phonon peak that was measured before plastic deformation. Annealing at the higher temperatures used during titanification, similar to that carried out on SRF cavities, recovered the lost phonon peak and increased the Kapitza conductance by 300%. Thermal conductivity measurements of single and bi-crystal niobium samples are also reported in this ongoing research.

INTRODUCTION

Niobium superconducting radio frequency (SRF) cavities are used to accelerate charged particles near the speed of light. These cavities have much lower losses than those made of copper, thus allows much higher average fields.

The thermal conductivity of Nb *k* plays an important role in the stability of the applied RF fields in the cavity. The thermal break down of a Nb SRF cavity from a temperature rise on a single defect is governed primarily by changes in *k* due to localized heating [1]. Using high purity Nb and limiting the quantity and size of defects address this problem. The purity of Nb is quantified by measuring its residual resistance ratio (RRR), which is proportional to *k* at temperatures near 4 K [1].

The situation differs, however, when the heating is uniform over an area with dimensions comparable to the material thickness, i.e. a case for "defect free" cavities, causing global thermal instability (GTI) [1]. Under these circumstances, losses, such as surface resistance, which has exponential surface temperature dependence, or electron heating from field emission, ultimately limits the maximum achievable gradients in the SRF cavity. Thermal-magnetic simulations for defect free cavities, as shown in Fig. 1 and also by Amrit *et al.* [2], have revealed that the temperature rise on the RF surface may only be a few hundred milli-kelvin, but is sufficient to limit the maximum allowable magnetic fields in the cavities. In this limit for defect free cavities, both the phonon thermal conductivity and Kapitza conductance *h* play vital roles in determining the initiation of GTI.

While the thermal conductivity above ~4 K is well known and correlated with RRR, for temperatures below ~3 K the correlation is lost due to phonon conduction. In this regime, the microstructure of the material plays an important role in determining its phonon thermal conductivity. Plastic deformation has a pronounced effect on *k*. Wasserbäch et *al*. [3] have found that *k* is reduced by a factor of about 40 (at T=1 K) in a high purity single crystal Nb sample (RRR 10500) that is uniaxially strained 36%, as compared with an undeformed specimen. Similar thermal conductivity behaviour at temperatures below 4 K may be expected in Nb SRF cavities, which are routinely fabricated through plastically deforming the metal during the deep drawing process.

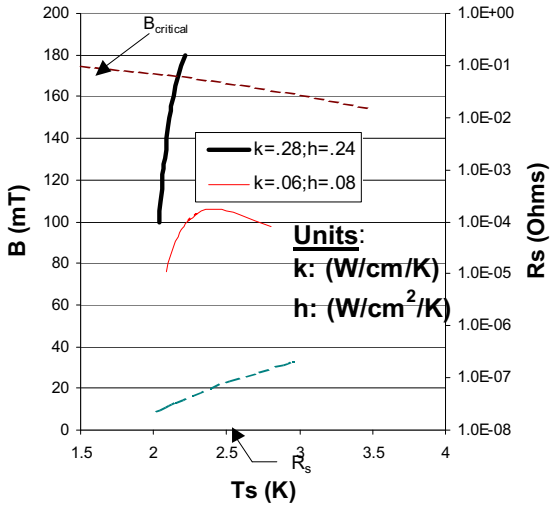

Figure 1: Thermal-magnetic simulations with constant thermal properties, *k* and *h*, for the two cases are shown. About a five times increase in *k* and a three times increase in *h* resulted in almost 50% improvement in applied magnetic fields. Parameters used for these simulations are R_{res} = 5 nohms, t = 3 mm, T_b = 2 K, f = 1.3 GHz, RRR = 230. The scale on the right is for surface resistance.

The deformation-induced decrease in *k* and *h* of Nb are reported in this study, as well as their recovery through annealing at low and moderate temperatures.

SAMPLE PREPARATION

Test results from three sets of samples, i.e. cylinders (Tokyo Denkai with Ingot RRR ~232), flat rectangular plates (Wah Chang with RRR ~300), and single/bi crystals (CBMM with RRR ~280) are reported here.

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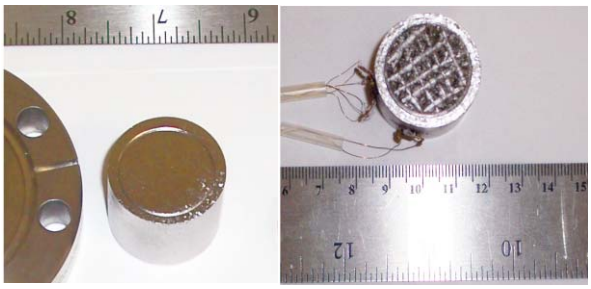

Figure 2. Left view shows the surface state of cylinder sample 1, while the right view shows the cylinder sample 2 having surface index (SI) > 3. Here SI is defined as the ratio of exposed surface area to the projected area.

For the two cylindrical samples, as shown in Fig. 2, measurements of k and h are reported. For the two rectangular flat plate and the two single/bi-crystal samples, however, only measurements of k are reported. Table 1 summarizes the details of the preparation of these three sets of samples.

Table 1: Samples Preparation Details

Sample	Treatment
Cylindrical Sample 1	3% strain
	Titanification
Cylindrical Sample 2	Surface deformation SI > 3
	Titanification
Flat plate samples	750 °C heat treatment
	Titanification
Single/Bi crystal samples (EDM cut)	Baseline measurements

The low temperature heat treatment at 750 °C lasted for 2 hrs, whereas the titanification process was carried out at 1300 °C for 2 hrs and then at 1200 °C for 4 hrs.

EXPERIMENTAL SYSTEM

The cylindrical Nb samples (3 cm dia. by 3 cm long) are mounted on the sample holder, as shown in figure 3, and placed in an evacuated chamber assembly. Three in situ calibrated carbon sensors, attached along the length of each sample, are used to measure the temperature rise in the sample when a dc heat load is applied to its one end through a thin foil heater. The other end of the sample is exposed to liquid helium (LHe) contained in a stainless steel tube, as shown in figure 3. This experimental arrangement has the advantage of measuring both the thermal conductivity as well as the Nb - LHe interface heat transfer coefficient in the same experimental run. The interface temperature is estimated by linear extrapolation. Additional details are presented in [4].

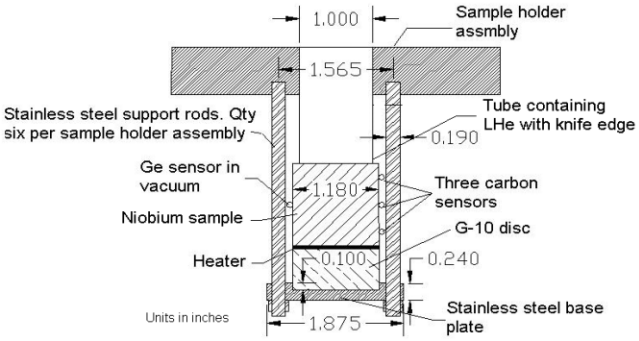

Figure 3. Experimental configuration for a cylindrical Nb sample. The sample holder assembly has a Nb sample with heater on the bottom side and stainless steel tube with knife-edge containing liquid helium on the other side.

For the flat plate and the single/bi-crystal samples, the sample holder assembly, as shown in Figs. 4 and 5, respectively, is simply a blank conflat flange. A right angle bend is made at one end of the flat plate sample to attach the sample to the flange using a brass screw. The heater on the other end of the sample provides the specified input heating. Using the same evacuated chamber with an arrangement of three collinear carbon sensors, similar to those for the cylindrical samples, the measurements for thermal conductivity of these samples are made. Total error in the measurements of thermal conductivity from all the three experimental arrangements and in the Kapitza conductance measurements, is less than 10%.

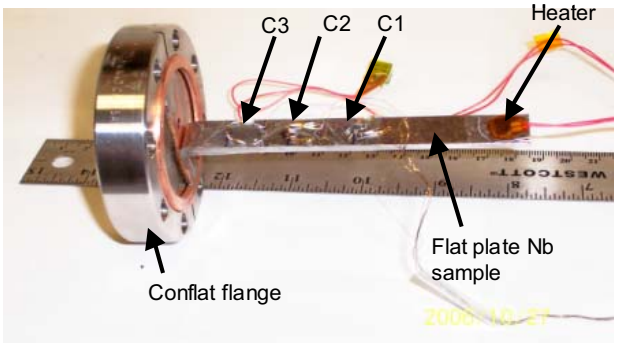

Figure 4. Flat plate experimental configuration. Nb sample of size 11 X 1.4 X 0.3 cm has three in-line carbon sensors with a thin foil heater on one end and conflate flange on the sink end.

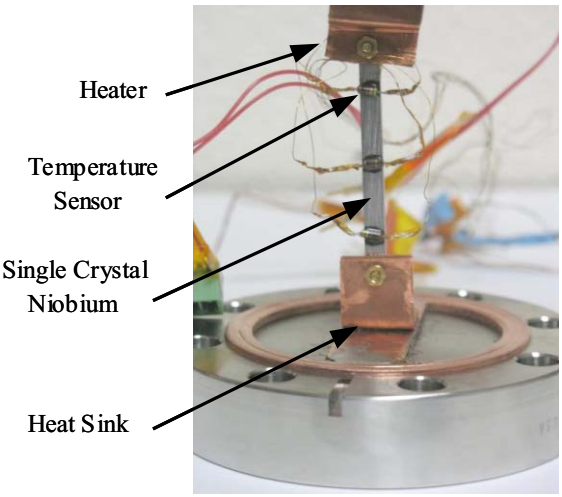

Figure 5. Experimental arrangement for measurements of k for the single / bi-crystal samples (0.3 X 0.3 X 3.0 cm).

RESULTS AND DISCUSSION

Thermal conductivity measurements

Thermal conductivity measurements of small grain Nb samples 1 and 2 are shown in Figs. 6 and 7, respectively. As expected, in the as received states, both of the figures for the cylindrical samples clearly reveal the formation of a phonon peak at approximately 2 K with a local minima forming at near3 K.

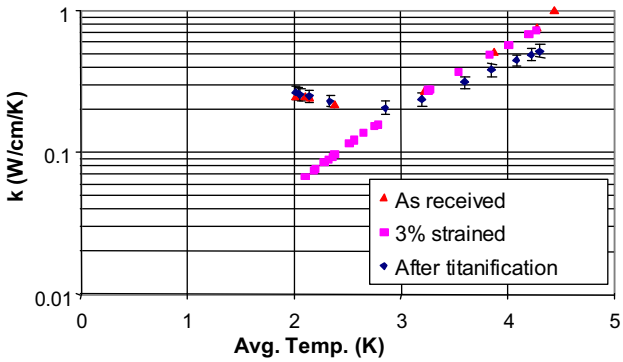

Figure 6. Measured values of k of cylindrical sample 1 are compared for the as received material against two of its later treatments.

After inducing plastic deformation (e.g., approximately 3% nominal strain ($\Delta L/L$) in sample 1), both samples lack a phonon peak, resulting in almost five-fold reduction in k at 2 K.

After titanification of the two samples, although the phonon peak in k was recovered to its as received value, no significant changes are measured above 3 K.

Because the measurements of k for the two flat plate samples were identical to each other, therefore, the results of only one sample are presented here, to avoid repetition.

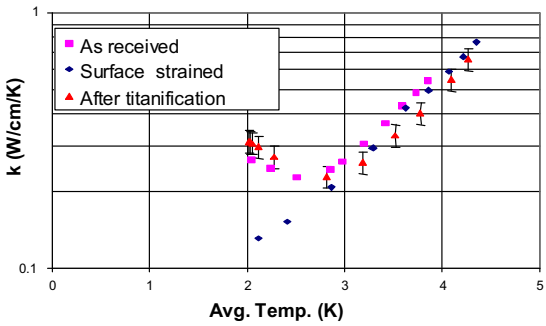

Figure 7. Measured values of k of cylindrical sample 2 are compared for the as received material against the two of its later treatments.

In the as received state, as shown in Figure 8, measured values of k of the flat sample show no signs of formation of phonon peak at around 2 K. However, a small kink in the conductivity near 3 K can easily be seen.

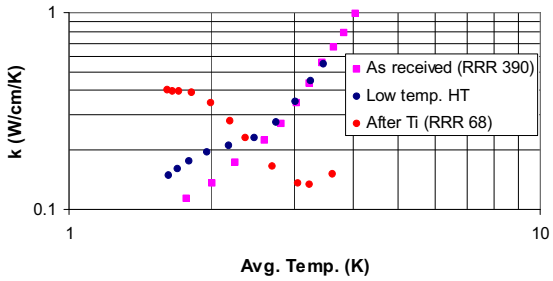

Figure 8. Thermal conductivity measurements of flat plate samples are compared for 'as received' state against two heat treatments carried out on them.

After low temperature (at 750 ^{o}C for 2 hrs) heat treatment, the kink below 3 K became more pronounced without forming a phonon peak and without any significant changes in k above 3 K. After titanification of the samples at moderate temperatures, formation of phonon peak is clearly visible near 2 K, but a significant and unexpected drop in k occurs above 3 K. Corresponding to k at 4 K, the estimated RRR is about 80 rather than the expected RRR of 600 from the titanification process. To confirm this drop, the sample was twice subjected to RRR measurements. Both resulted in RRR 67 with ±20% error. The RRR measurements thus confirmed the thermal conductivity measurements. The exact cause for this drop in RRR value after titanification is not known, other than an unexpected anomaly during titanification.

A baseline measurement of k is shown in Fig. 9 for a single crystal sample and a bi-crystal sample, in a logical extension of these measurements. The legend in Fig. 9 shows two sets of measurements for each sample from two pair of sensors (i.e., from sensors 1-2 and from

sensors 2-3). The four measurements are in agreement. Except for a small increase in *k* measured below 3 K, no significant formation of a phonon peak can be observed in either of the samples. Further measurements are thus needed after the annealing of these single / bi crystal samples.

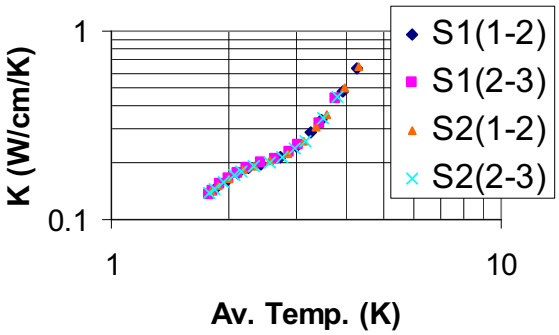

Figure 9. Baseline measurements of *k* for a single crystal sample and a bi-crystal Nb sample are shown to be identical within the limits of experimental error.

Kapitza Conductance Measurements

Kapitza conductance measurements of cylinder samples 1 and 2 for different surface conditions, as shown in Figs. 10 and 11, respectively, are compared with values from the literature [5]. As shown in Fig. 10, despite 3% strain induced in the sample 1, the Kapitza measurement values do not change from its as received state.

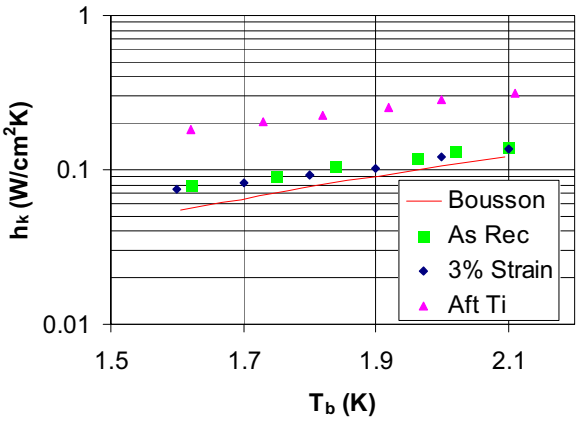

Figure 10. Kapitza conductance measurements of cylindrical sample 1 are compared for the as received sample against the two of its later treatments

This is possibly because of a light buffer chemical polish (BCP) etch (10-15 μm) that was carried out before the measurements, thus making the two surfaces identical. After titanification followed by a ~50 μm BCP etch on cylinder sample 1, however, an approximately twofold improvement in *h* is measured at 2.1 K.

To analyse the effect of increased surface area (SI > 3) on Kapitza conductance, the surface of cylinder sample 2 was prepared, as shown in Fig. 2 (Right view), by pressing a stainless steel knife-edge against it. Subsequently, a light BCP etch (10-15 μm) was done to clean the surface. However, as compared with the as received state, as shown in Fig. 11, the measurement for the deformed surface with SI>3 did not result in proportionally increased *h*. Although *h* is measured to increase by about 50% at 2.1 K, it is insufficient to cater for the increased surface area. No simple explanation can be provided to this unexpected result, although the effect of surface deformation on phonon transmission may cause such behaviour.

After the low temperature heat treatment at 750 °C for 2 hrs, there is a measured increase in *h* of 100% at 2.1 K from its deformed value, which further increased by about 20%, at the same temperature, after titanification. Thus the total increase in *h* of the cylinder sample 2 is more than three fold from its as received condition.

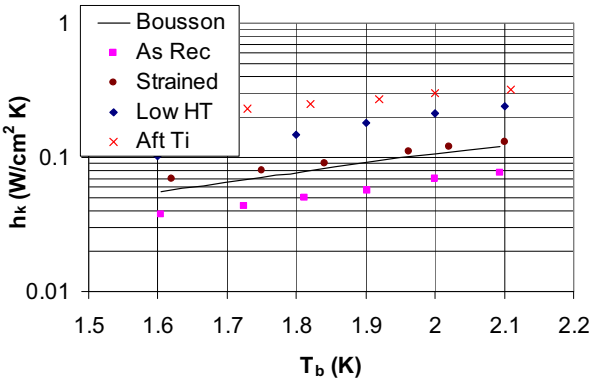

Figure 11. Measured values of *h* for cylindrical sample 1 are compared for as received sample against the two of its later treatments

CONCLUSIONS

Phonon peak in Nb

This study revealed that the strains induced through plastic deformations reduced *k* of Nb by 80% at 2 K, with a correponding loss of the phonon peak. Low temperature annealing (at 750 ˚C for 2 hours) was found to be insufficient to recover the lost phonon peak. However, titanification done at about 1300 ˚C restored the lost phonon peak near to its as received value.

Simple numerical computations performed in this study reveal that the effect of recovery of the lost phonon peak along with improved Kaptiza conductance resulted in an approximately 50% improvement in the applied magnetic fields for the case of a defect free 1.3 GHz cavity operating at 2 K. Thus, the need for titanification of cavities is found to be a necessary step in the preparation of high frequency cavities resulting in improved performance through enhanced phonon peak and significantly increased Kapitza conductance.

Kapitza conductance

The effect of the large surface index (increased surface area) on *h* remains inconclusive, possibly due to

other effects influencing the heat transfer. These include, but are not limited to, the effect of surface deformation and BCP etching on the Kaptiza conductance. Although, both the low and moderate temperature annealing have shown a consistent increase in Kapitza conductance, the exact cause of this increase is still undetermined. Further research in this direction is needed to find the exact cause of increase in Kapitza conductance after annealing.

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