Thermal conductivity of 2G HTS wires for current lead applications

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Abstract. We have studied the thermal conductivity of several 2G HTS coated conductor wires produced by AMSC’s RABiTS™/MOD processes. The measurements employed a non-steady state method in which the sample is connected to a cold head on one end and a copper block on the other end. The heat capacity of the copper block is used to determine heat flow through the sample as the cold head slowly warms up. Measurements were done at temperatures ranging from 10 K to 130 K on 2G wires made with a Ni 5at%W substrate and different lamination architectures. The focus of the investigation was on the effects of lamina material type, thickness of the silver layer and alloyed silver. The data show that 2G wires can be 3 times less thermally conductive when compared to 1G BSCCO wires with a Ag-Au matrix, making them excellent candidates for use in current lead applications.

1. Introduction

Current leads are used to transmit current from room temperature power sources to cryogenic systems such as superconducting coils and magnets. Heat leakage into the cryostat through the current lead is a significant portion of the overall cooling load and for many applications current leads made from normal metal conductors are much too thermally conductive. High temperature superconductors (HTS) are well suited for current lead applications due to their high electrical conductivity and low thermal conductivity. A number of workers have reported on HTS current leads based on BSCCO (i.e., first generation or 1G) superconductors [1-2]. Second generation or 2G YBCO HTS conductors with their layered structure of predominantly low conductivity alloys show even more promise for very low thermal conductivity current leads.

In this paper we present thermal conductivity data of a variety of 2G wires with different architectures. The measurements were made using a transient method that provides accurate results without the long times typically required of steady-state techniques. We also present heat leak data on a prototype current lead constructed with 2G wire that was optimized for low thermal conductivity. The results demonstrate the high potential of AMSC’s 2G wire for use in current leads.
2. Experimental

Thermal conductivity is usually determined using a steady-state method by applying a constant heat flow \( \frac{dQ}{dt} \) to a sample and measuring the temperature gradient \( \frac{\Delta T}{\Delta l} \) that develops along its length. The steady state thermal conductivity \( k \) is calculated using:

\[
k = \frac{Q \cdot \Delta l}{A \cdot \Delta T}
\]

where \( A \) is the sample cross-sectional area. This method utilizes the exact solution of the heat conduction equation and is a direct measure of thermal conductivity. It requires a careful and precise experimental technique in order to achieve accurate results as demonstrated in [3] where a 4%-6% accuracy was achieved. The steady-state method is also relatively slow since the time required to reach thermal equilibrium limits the speed with which the measurements can be made.

In this work, we chose to use a transient technique [4] that provides a good compromise between accuracy and measurement time (1-2 samples per day) and can be easily implemented in standard cryo-coolers without adding much complexity. Figure 1 shows the experimental setup.

![Figure 1: Experimental setup](image-url)

For this measurement technique, the sample is connected at one end to the cold head of a 2 stage cryo-cooler (Cryomech Inc., Model PT405) while on the other end an OFHC copper block is attached (\( m=2g \)) which acts as a heat sink. Two silicon diode temperature sensors (Omega CY7-SD7) are soldered with InBi-solder to the sample 28mm apart and another sensor is soldered to the copper block. The error in the temperature reading produced by the solder joint is regarded as negligible as the thermal conductance of solder joints according to Ekin [11] are an order of magnitude higher than the thermal conductance of the materials investigated. To minimise radiation errors the sample is surrounded by a copper shield that is attached to the cold head. The setup is housed in a standard vacuum chamber which is evacuated to \(<10^{-6} \text{ mbar}\) prior to cooling the sample. The sample is cooled to 4K and then slowly heated (\( \frac{dT}{dt} \sim 5 \text{ mK/s} \)) by the heater mounted on the cold head. The heat flow is determined by the temperature change of the copper heat sink using:

\[
\dot{Q} = m \cdot c(T) \cdot \frac{dT}{dt}
\]

where \( m \) is the mass and \( c(T) \) is the specific heat of copper block [5-6]. With the measured temperature gradient along the sample, the thermal conductivity can then be obtained using (1).
Figure 2 shows data obtained with this method on 1G wire (CryoBlock™) from AMSC compared to measurements done on the same material by Schwarz et al. [7].

![Figure 2](image)

**Figure 2.** Comparison of data on AMSC 1G Cryoblock wire obtained by Schwarz et al. (square) and with the described transient method (circles).

This procedure uses a steady-state equation even though the system is always slightly off equilibrium and this approximation requires an error estimate to gauge the accuracy of the results. The main problem is due to the finite heat diffusivity within the sample that results in an exaggerated temperature difference since heat flow near the cold end sensor lags behind that near the heat source. However, if the time required to transfer heat between the sensors can be calculated, the error in the temperature gradient can be estimated by multiplying that time with the known $\frac{dT}{dt}$. As shown in [8] the timescale for an insulated rod of initially homogeneous temperature to come to equilibrium when heated with a constant amount of heat on one end is:

$$t = \frac{Z^2}{4 \cdot D}$$  \hspace{1cm} (3)

where $Z$ is the length of the rod and $D$ the diffusivity of the material. As most of the HTS samples examined are composite structures consisting mostly of stainless steel (SS), the time scale can be estimated using literature properties for stainless steel [9]. With the thermal conductivity $k$, the specific heat $c$ and the density $\rho$ the diffusivity of stainless steel can be calculated using:

$$D = \frac{k}{\rho \cdot c}$$  \hspace{1cm} (4)

Since the temperature sensors add thermal mass to the system, they also introduce an error that can be treated similarly. Assuming the thermal properties of the sensors are similar to SS, the error according to (4) would increase by an amount proportional to the added mass, which is about 17% of the sample mass. On the other hand, since the sensors are designed for fast response, this combined error estimate can be seen as an upper limit. Therefore with the given heating rate and the temperature dependence of the diffusivity, the resulting error estimate is 7-12% at temperatures above 30K and 12-19% in the range 10-30K.
3. Results and discussion

The 2G wire samples were provided by AMSC and details of the laminated wire architecture are described elsewhere [10]. The main components contributing to the thermal conductivity are the Ni-5at%W substrate (thickness ~75µm), a silver coating (thickness 2-4µm) around the substrate, and metal stabilizer strips (various thicknesses) on both sides. Since the stabilizer strips are soldered to the substrate wire, the thickness of the solder layers (~10µm) must also be considered. The contribution of the buffer and YBCO layers to heat transport is assumed to be negligible. For 2G wire, the two key components affecting thermal conductivity which are selectable and to some degree controllable are the type and thickness of the stabilizer layers and the thickness of the Ag coating.

Figure 3 shows a comparison of the thermal conductivity of various wires made with different stabilizer materials and thicknesses. The thermal conductivity values of these wires ranged from 10 to 70 W/m·K. A peak around 30 K is present in all samples and can be attributed to the silver layer. Although sample-to-sample variability of the silver and solder thicknesses can make comparative evaluations difficult, some significant trends are clear. As expected, brass laminated wire shows the highest conductivity and stainless steel clad wire is clearly favourable for low thermal conductivity. Also, the type of plating used on the stabilizer strips (to improve solderability) plays a role with Sn performing the best.

![Figure 3](image_url)

**Figure 3.** Thermal conductivity of different 2G wires varying in stabilizer type and thickness

In the temperature range between 10K and 80K silver is the dominant source of thermal conductivity and since this is the range where most current leads operate, reduction of the silver layer’s contribution to heat transfer is critical. To look more closely at the effects of reduced silver content, two wires with 75µm stainless steel stabilizer were used to study the impact of a 25% reduction of Ag thickness from 4µm to 3µm. Aside from the different silver thickness, both samples underwent identical processing.

Figure 4 shows the results for these two wires. The difference in thermal conductivity of ~3 W/m·K is constant over the whole temperature range and these data illustrate the significant role the silver plays in thermal conductance: a 1 µm reduction in silver thickness represents a ~0.5% reduction in the overall thickness of the wire but results in a roughly 15% reduction in thermal conductivity.
The data from these wires was used to do a simple calculation of the thermal conductivity of the laminated structure using the formula:

$$k = \frac{\sum k_i \cdot A_i}{A}$$  \hspace{1cm} (5)

where $k$ is the thermal conductivity and $A$ the cross-sectional area of each component $i$. Using the literature values of stainless steel [9] and solder [11] along with the substrate data, one can calculate the expected thermal conductivity due to the primary components. By subtracting this value from the overall conductivity of the sample with a 4µm silver layer, the silver contribution can be obtained.

**Figure 4.** Effect of varied silver thickness on samples with 75µm stainless steel laminate. Black open squares refer to a 4µm silver layer red open circles to a 3µm silver layer. The difference in thermal conductivity between the two samples is also plotted.

**Figure 5.** Thermal conductivity of 2G wires with varying Ag thickness, NiW substrate, and stainless steel laminate along with calculated values for the combined substrate+laminate and a wire with 25% reduced silver thickness.
Using this calculation the thermal conductivity of the silver layer was determined to be about 400 W/m·K above 80K with a peak value of 650 W/m·K at 30K. This result is in good agreement with data Schwartz [7] reported for silver layers of similar thickness and indicates a RRR value of less than 30 [12]. The thermal conductivity of the sample with 3µm Ag was then calculated using (5) and compared to the data of Figure 4. The model shows good agreement with the measured data. The result shows that the thermal conductivity can be calculated reasonably accurately if the layer thicknesses are known (Figure 5). It also shows that even with a reduced silver thickness, the overall thermal conductivity remains relatively high in the temperature range relevant for current leads.

Of course there are limits to which the silver coating thickness can be reduced without affecting other properties of the HTS wire, so it makes sense to try an approach similar to that used on 1G CryoBlock wires in which thermal conductivity was reduced by using a silver alloy instead of pure silver. To explore this possibility, several 2G wires were processed with silver alloy layers and measured for thermal conductivity. The performance of this 2G “CryoBlock2™” wire is shown in Figure 6. Compared to a standard stainless steel 2G wire with reduced silver layer thickness, the thermal conductivity of CryoBlock2 wire is reduced by 10-15% at temperatures over 70K and up to 35% in the low temperature range. The low temperature performance gain is mainly due to the absence of a peak for CryoBlock2 wire. The inset in Figure 6 shows that CryoBlock2 wire significantly outperforms 1G CryoBlock wire, with thermal conductivity that is 1/3 or less over almost the entire temperature range.

To further verify the thermal performance of CryoBlock2 wire, a prototype current lead was assembled and its overall heat leakage measured. The body used a standard 100A G10 cylinder from HTS-110 in which a 250mm long CryoBlock2 wire was soldered (Figure 7). The current lead was attached to the cold head of the cryocooler on one end with a resistive heater and a temperature sensor attached on the bottom end. After cooling the entire current lead to 4.2K, heat was applied so that the bottom end stabilized at 64K while the top end was kept at 4.2K. The heat flow required to keep the temperature distribution in steady state is the heat leak.
To evaluate the contributions of the G10 body and CryoBlock2 wire, both an empty body and the assembled current lead were measured. The experimental results were compared to the conductive heat leakage using available thermal conductivity data for G10 [9] and calculated with:

$$\dot{Q} = \frac{A}{l} \int_{4K}^{64K} k(T)dT$$  \hspace{1cm} (6)

where $l$ is the current lead length. The results are shown in Table 1.

**Table 1.** Conductive heat leak of current leads made with CryoBlock2 wire

|                  | Calculated | Experimental |
|------------------|------------|--------------|
| G10 body         | 4.3mW      | 4.7mW        |
| CryoBlock2 wire  | 3.8mW      | 3.7mW        |
| Current lead     | 8.1mW      | 8.4mW        |

4. **Conclusion**

We have demonstrated a transient method for measuring thermal conductivity that has a fast turnaround time and accuracy which is on a par with steady state techniques. We used this technique to evaluate a variety of 2G wires and confirm the expected lower thermal conductivity of 2G wire compared to 1G. This method was also used to evaluate a new 2G wire - CryoBlock2™ - with an optimised architecture comprised of stainless steel stabilizer and a silver alloy coating on the HTS layer. The performance of CryoBlock2 wire was found to be far superior to that of 1G CryoBlock wire. The thermal conductance of CryoBlock2 wire in the 10K - 64K temperature range is reduced by a factor of 3 or more compared to 1G material. Furthermore, a prototype current lead made with CryoBlock2 wire had a conductive heat leak of about one half that of a similar ampacity 1G current lead. These results indicate that CryoBlock2 wire is a very promising material for ultra low heat leak current leads.

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