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Comparison of copper and aluminum as the thermal link material for conduction-cooled accelerator cavities

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Abstract. Cryocooler conduction-cooling has recently emerged as a new frontier for cryogenic cooling for superconducting radiofrequency (SRF) cavities. In this scheme, an SRF cavity is mechanically coupled to a closed-cycle cryocooler using linkages made of high thermal conductivity metals. In this note, we compare the thermal transport properties of high purity aluminum and high purity copper as applied to SRF cavity conduction cooling. We show that copper can enable faster cooldown than aluminum from room temperature to the base temperature near 4 K and behave equally well or better during steady state cavity operation near the base temperature.

1. Introduction

Superconducting radiofrequency cavities are a workhorse of modern day particle accelerators (for example, [1]) and are recently being gaining traction for certain industrial applications of electron beam irradiation [2,3]. SRF cavities cooled conductively using closed-cycle cryocoolers are the key enabler for the latter. In this cooling scheme, an SRF cavity is mechanically linked to the cryocooler using metallic 'thermal' links with high thermal conductivity near the base temperature of cavity operation, which is ~4 K. The metals are mainly high purity aluminum [4-8] and high purity copper [9,10], which are selected primarily based on the thermal conductivity near 4 K, i.e., on how well they will remove heat from the cavity during its steady state operation. Although this is an important operating parameter, the choice should also be made considering the time the cavity will take to cool down from room temperature to the base temperature, the method used to connect the thermal links with the cavity (mechanically bonded or bolted), etc. In this note, we present a comparison of thermal transport properties of high purity copper and high purity aluminum with a focus on the cooldown time. The comparison also includes in-house measured thermal contact resistance data of copper and aluminum links as mechanically bolted to a niobium SRF cavity.

2. Comparison of copper and aluminum

a. Thermal conductivity

A cryocooler conduction-cooled SRF cavity begin operation at room temperature and gradually cools down to the base temperature. The rate of cooldown depends on the total thermal energy that is to be removed and the rate at which this thermal energy is removed. For our comparison, we assume that the same niobium SRF cavity is cooled using linkages made of copper and aluminum, so that the thermal energy to be removed (integral of cavity heat capacity multiplied by the change in temperature, *i.e.*, 300 K → 4 K) is the equal for the two cases. The cooldown rate is then governed by the thermal conductivity of the linkage material.

Figure 1 is a comparison of thermal conductivity of several purity grades of aluminum and copper between 300 K and 1 K [11,12] (with aluminum in the normal conducting state). The purity grades are defined using residual resistivity ratio or RRR. For similar RRR, the thermal conductivity of copper is higher than that of aluminum over temperatures 1 – 10 K. This implies that copper is better at transporting heat away from the cavity during steady state operation near 4 K. Furthermore, at warmer temperatures 100 – 300 K, thermal conductivity is independent of purity level and copper has nearly two fold thermal conductivity than of aluminum. Therefore, copper will also enable faster cooldown of the cavity than aluminum. Thus, overall, copper is thermally superior to aluminum.

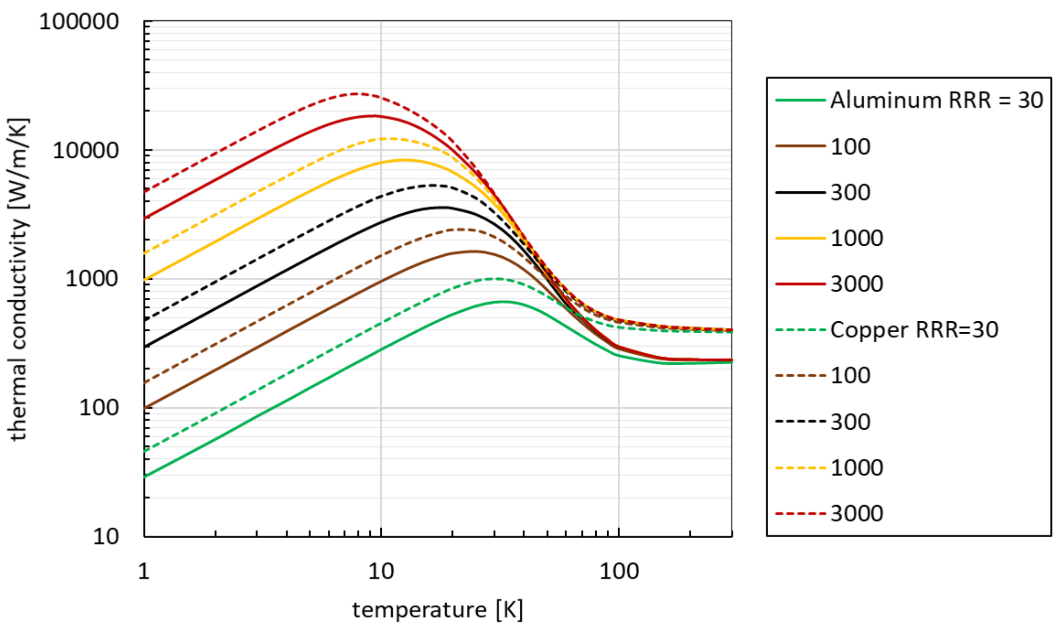

Figure 1. Comparison of thermal conductivity of copper and aluminum for several purity levels (data sourced from [11] and [12]).

b. Thermal contact resistance

Thermal contact resistance between the SRF cavity body material (niobium) and thermal linkage material (high purity aluminum or high purity copper) is also important for configurations comprising bolted connection between the cavity and thermal link. Smaller thermal contact resistance is better as it produces a closer thermal equilibrium between the two.

Figure 2 compares thermal contact resistance at bolted joints of niobium-aluminum and niobium-copper measured at Fermilab. These preliminary data are for three values of applied bolting force (tension) applied on square shaped contacts of apparent area 5.9 cm^2. The tensions correspond to full flat load of belleville disc springs used on the joints. The contacts were 'dry', *i.e.*, without any thermal grease or indium foil.

We note from these preliminary data that aluminum contacts possess lower thermal resistance at the lowest applied tension while the difference between aluminum and copper contacts diminish at the highest applied tension. Copper, therefore, is not drastically different than aluminum from the point of thermal contact resistance. The contact resistance can be further reduced by using thermal grease and/or thin indium foil interposed at the contact. Future measurements will include these combinations.

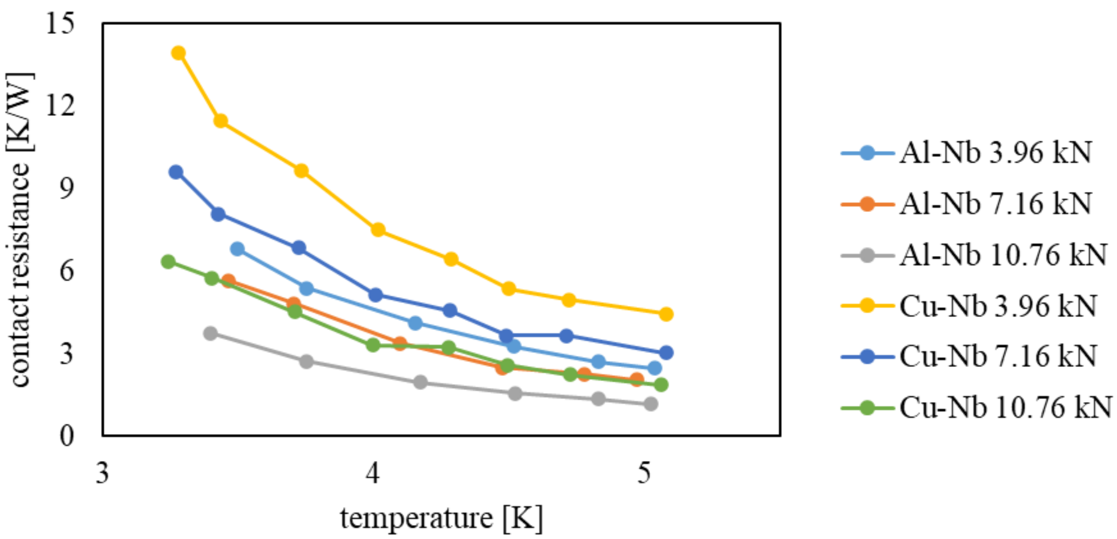

Figure 2. Experimental data on thermal resistance of niobium-aluminum and niobium-copper bolted joints of 5.9 cm^2 apparent contact area. The data are accurate with 10%.

In addition to bolted joints with niobium, a thermal link may comprise bolted joints of aluminum-aluminum and copper-copper. Thermal resistance of such contacts are summarized in reviews by Gmelin *et al.* [15] and Dhuley [13]. Thermal resistance of braided flexible linkages can be estimated from [14].

3. Summary

A comparison between thermal transport properties revealed that copper of similar purity as aluminum can lower the cooldown time of niobium SRF cavities when conductively cooled using cryocoolers. Preliminary measurements show that aluminum-niobium contacts possess slightly lower thermal resistance than copper-niobium bolted contacts. However, the difference diminished with the applied tension on the contact, making copper-niobium joints equally viable as aluminum-niobium contacts. Further improvement can be brought about by interposing the contacts with thermal grease and or indium foil.

Acknowledgement

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