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# A flexible high-current lead for use in high-magnetic-field cryogenic environments

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A flexible high-current lead for use at cryogenic temperatures and in high-magnetic fields has been developed using high purity aluminum. Readily available high purity aluminum has distinct advantages over copper, namely lower resistivity at liquid-helium temperature, lower magnetoresistance, lower yield stress, lower density, lower cost for material with comparable conductivity, and room temperature annealing. Aluminum may also be used in high magnetic fields, where flexible superconductors cease to function. Practical issues encountered in the design and fabrication of such flexible leads are discussed, such as geometrical considerations where sample loading and heating are important issues. © *1999 American Institute of Physics.* [S0034-6748(99)03908-8]

## I. BACKGROUND

Many cryogenic measurements require a flexible lead for high-current injection. In the example discussed here, precise electromechanical measurements of superconductors[1,2] require relief of prestress from the differential thermal contraction between a superconducting sample (effectively copper), and a stainless-steel support structure. The solution has general applicability to situations where a flexible lead system is needed that can handle high current. The essential element is a hyperconducting aluminum lead, which can be very thin, and therefore flexible, and still have a high-current capacity at low temperature.

## II. PROPERTIES OF HIGH PURITY ALUMINUM

Although aluminum has about 1.6 times greater resistivity than copper at room temperature, high residual resistance ratio ($\mathrm{RRR} \equiv \rho_{293\,\mathrm{K}}/\rho_{4\,\mathrm{K}}$) is more readily obtained in aluminum than copper. In particular, high purity ($>99.9995\%$) aluminum with a RRR on the order of 5000 is commercially available at reasonable cost. Such an aluminum conductor with a typical room temperature resistivity of $2.8\times10^{-6}\,\Omega\,\mathrm{cm}$ will have a resistivity of only $5.6\times10^{-10}\,\Omega\,\mathrm{cm}$ at liquid-helium temperature, while the resistivity of readily available OFHC (oxygen free) copper ($\mathrm{RRR}=70$, $\rho_{293\,\mathrm{K}}=1.72\times10^{-6}\,\Omega\,\mathrm{cm}$) is roughly 44 times greater at 4 K.[3] This facilitates the fabrication of very thin aluminum leads with high current capacity and low heat generation. Because the resistivity of aluminum has a power-law dependence on temperature, high values of RRR mainly appear in the region below 30 K.[4] As a result, at liquid-nitrogen temperatures and above, aluminum loses its advantage over copper. For a very pure aluminum sample ($\mathrm{RRR}=7000$), we found a resistance ratio ($\mathrm{RR} \equiv \rho_{293\,\mathrm{K}}/\rho_{77\,\mathrm{K}}$) between room temperature and 77 K of 13, which is consistent with literature values.[5] The uncertainty in this RR measurement is approximately ±5%. (This RR will not change much for materials with $\mathrm{RRR}>1000$.) On the other hand, the RR of copper is 8.5, which makes it a slightly better conductor than aluminum at this temperature, because of its lower $\rho_{293\,\mathrm{K}}$.

In applications where mass is critical, aluminum offers low density. The density of aluminum is 3.3 times less than that of copper,[6] giving aluminum 145 times the current capacity of the same mass of copper at 4 K and nearly three times the capacity at 77 K.

Aluminum also has a lower magnetoresistance than copper.[7] The rate at which the resistance of aluminum rises with transverse magnetic field diminishes substantially between 1 and 2 T, whereas the resistance of copper continues rising at a steep rate. This characteristic makes aluminum favorable in high field environments.

Most flexible leads undergo mechanical fatigue through bending. Although the resistance of many metals increases with fatigue, aluminum has annealing properties that mitigate this effect. Figure 1 is a plot of RRR recovery in aluminum for various annealing temperatures. Full recrystalization (100% RRR recovery) can be achieved through a vacuum annealing at 350 °C for 1 h, followed by slow cooling for several hours.[8] Substantial recovery also occurs at typical soldering temperatures and even at room temperature. The alloy 91 mass % Sn–9 mass % Zn is an excellent eutectic (199 °C) solder for aluminum. We found that if the lead is held at this temperature for 1 h following repetitive strain at room temperature, the Al can recover 87% (±5%) of its maximum RRR. Aluminum also moves toward the strain-

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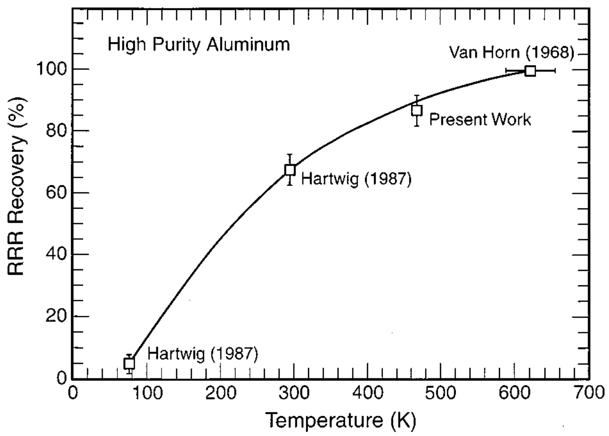

FIG. 1. Percent RRR recovery in high purity aluminum ($300<\mathrm{RRR}<7000$) for a 1 h anneal at various temperatures. The percent recovery indicated on this curve is independent of the fatigue imparted to the material.

free (annealed) state at room temperature, recovering about 70% of the original RRR after 1 h.[9]

Although extreme purity aluminum is available with RRR above 40 000, as the purity and RRR increase above 5000, so do sensitivity to fatigue and magnetic field. Consequently, the benefits of materials with RRR above 5000 are rarely realized.

Superconductors such as $Nb_3Sn$ and high-temperature superconductors (HTS) such as Y–Ba–Cu–O are capable of operating in high magnetic fields (18 T for $Nb_3Sn$ and much higher for HTS), but their brittle nature hinders their use as a flexible lead. Conversely, more flexible superconductors such as Nb–Ti can be operated only in fields up to 10 T.

## III. CURRENT LEAD MECHANICAL DESIGN

Figure 2 is a schematic drawing of the flexible current lead and its position in the apparatus. A rectangular cross section was chosen for the flexible lead in order to minimize stiffness in the transverse direction, yet maximize its cross-sectional area. The moment of inertia of such a beam about its width is given by $I=wt^3/12$, where $w$ is the width and $t$ is the thickness of the lead.[10] The deflection $y$ of a bar of length $l$ with one end fixed is

$$y=\frac{1}{3}\frac{Fl^3}{El}=\frac{4Fl^3}{Ewt^3}, \tag{1}$$

where $F$ is the force on the free end and $E$ is Young's modulus.[11] Young's modulus for aluminum at 4 K is 78 GPa.[12] In our example, the deflection of the beam is 0.4 mm and arises from the differential thermal contraction between the sample and the stainless-steel support. Assuming we want to keep the axial force on the sample less than 1 N, the thickness of a 3 mm wide by 9 mm long beam must be less than 0.31 mm. The length of the flexible lead must be aligned parallel to the magnetic field to avoid a Lorentz force on the lead. A copper block was soldered between the flexible lead and sample to increase the contact surface area and decrease the contact resistance.

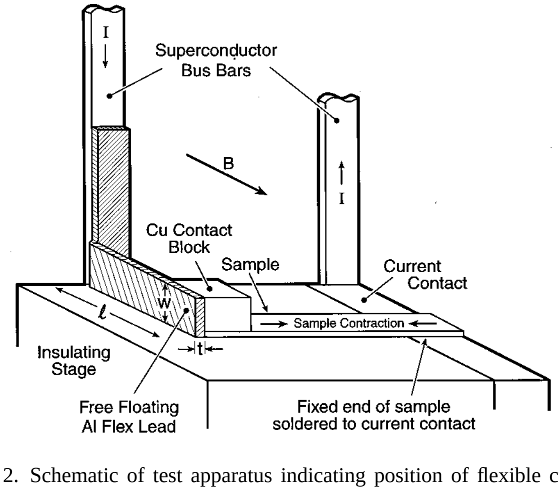

FIG. 2. Schematic of test apparatus indicating position of flexible current lead and sample.

## IV. CURRENT LEAD THERMODYNAMIC ANALYSIS

Determining the acceptable heat generation within a current lead system requires a thermoelectric analysis that depends on the specific application's heat transfer characteristics. The Joule heating in the lead is given by $P=I^2R=I^2\rho l/(wt)$. Let us assume the worst case, that this heat flows unimpeded into the superconductor and that both the current lead and superconductor rise uniformly in temperature. Let us also assume that we limit the temperature rise $\Delta T_{\mathrm{cr}}$ of the superconductor to 10 mK (this corresponds to a change of less than 0.2% in the critical current of Nb–Ti at 4 K and 0 T, and less than 0.7% at 4 K and 8 T, for example[13]). Then the allowable heat generation is $q_{\mathrm{cr}}=hA\Delta T_{\mathrm{cr}}$, where $A$ is the total surface area of the lead and sample, and $h=1\ \mathrm{W/(cm^2\,K)}$ is the heat transfer coefficient for liquid helium at low heat flux, which occurs when $\Delta T<100\,\mathrm{mK}$ for liquid helium at atmospheric pressure.[14] (At higher heat flux in the nucleate boiling region, the effective $h$ is even higher, making this calculation more conservative, until film boiling sets in at a very high heat flux of $q=1\ \mathrm{W/cm^2}$.) For the example shown in Fig. 2, the total wetted surface area of the lead and sample is about 1 $\mathrm{cm^2}$, so we calculate $q_{\mathrm{cr}}=10\,\mathrm{mW}$. Thus, a very conservative limit on the current is

$$I_{\max}=\sqrt{\frac{q_{\mathrm{cr}}}{R}}\cong 190\ \mathrm{A}, \tag{2}$$

where $R=0.27\ \mu\Omega$ is the total resistance at 4 K of the aluminum lead with the geometry shown in Fig. 2, assuming a conservative RRR = 1000. This is a worst case for the acceptable current limit because, in practice, there will be a thermal resistance at the joint between the flexible lead and the sample. Also, heat will flow out the other end of the flexible lead into the supply bus. Since helium boils at a rate of 1.4 L/(h W), the 10 mW of power generated at the lead will boil off only 14 mL/h of liquid helium.

A similar analysis can be done at liquid nitrogen temperature (77 K). Using $h=0.3\ \mathrm{W/(cm^2\,K)}$ (for a nonporous surface),[15] the same dimensions discussed above

$(3\,\mathrm{mm}\times 9\,\mathrm{mm}\times 0.31\,\mathrm{mm})$, and increasing the allowable temperature rise to $\Delta T = 100\,\mathrm{mK}$ (because of the higher ambient temperature), we find that $q_{\mathrm{cr}} \approx 30\,\mathrm{mW}$ and $R = 21\,\mu\Omega$, so $I_{\max}$ decreases to about 38 A. (For liquid nitrogen, the film/nucleate boiling boundary is 10 W/cm$^2$.[16]) Nitrogen will boil off more slowly than helium, however, at a rate of 0.023 L/(h W). Thus the advantages of aluminum over copper are great at liquid-helium temperature, but the two materials are comparable at liquid-nitrogen temperature. To achieve a higher current capacity, the cross-sectional area of the aluminum lead can be increased while still retaining reasonable flexibility.

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