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THERMAL AND SUPERCONDUCTING PROPERTIES OF AN ALUMINIUM ALLOY
FOR GRAVITATIONAL WAVE ANTENNAS BELOW 1 K

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ABSTRACT

We report the measurements of thermal conductivity, specific heat, and critical temperature of the aluminium alloy 5056 in the range 0.05 K to 1.3 K. The absence of magnetic anomalies in the specific heat and the rather high thermal conductivity in the superconducting state would allow reasonably fast cool-down below 0.1 K of multiton gravitational wave antennas made of this material. On the basis of the measured properties, the desired refrigerator characteristics are discussed.

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1. INTRODUCTION

In order to gain enough sensitivity to detect gravitational wave bursts of extraterrestrial origin, it has been proposed to cool Weber-type aluminium antennas below 1 K temperatures^{1,2}). Such low temperatures are needed to reduce the thermal noise, which limits the antenna sensitivity when a quantum-noise motion detector is employed³). Furthermore, it has been suggested that the third generation of antennas should use a back-action-evading measuring system (quantum non-demolition measurements) and operate below 0.1 K antenna temperature⁴). This temperature range is accessible with continuously operating dilution refrigerators.

The problems of cooling a massive bar antenna to very low temperature can be divided into three levels:

- i) thermal properties of the bar material, which may determine the maximum tolerable heat leak and the time to reach the desired temperature (self-cooling);
- ii) thermal design of the refrigerator, which must be able to cool the bar reasonably quickly and to absorb the residual heat leak at the desired ultimate temperature;
- iii) acoustic interference of the refrigerator with the antenna system; acoustic properties of the bar material.

In the following we shall briefly discuss the points above, referring to the bar material aluminium alloy 5056 (5.2% Mg, 0.1% Mn, 0.1% Cr), which is known to exhibit suitable acoustic properties down to 4 K⁵).

- i) In considering the refrigeration ability of currently available dilution refrigerators, it is easy to show that the self-cooling of the bar material limits the cool-down speed more than the refrigerator does. The self-cooling of materials poses severe problems when significant magnetic anomalies exist in the specific heat. As examples we may cite the resistance wire material manganin, most (probably all) austenitic and martensitic steels, most ferromagnetic and antiferromagnetic pure metals, and many dilute alloys with magnetic ions. It is known that Mn and Cr in pure Al are not magnetic (or that their Kondo temperature is very high); however, there are no existing

specific heat measurements on the hard AlMg alloys which would ascertain the absence of magnetic anomalies due to Mn or Cr.

The thermal conductivity in the superconducting state may set a limit to the residual heat leak that may be tolerated on a Weber-type bar antenna, which can be contacted thermally only at the central section.

- ii) There have been no systematic studies of residual heat leaks to large masses. The ultimate temperatures of dilution refrigerators, however, have usually been determined rather carefully. If, in addition, the temperature dependence of the cooling power has been measured near the ultimate limit, the residual heat leak (which, by definition, is external to the refrigeration cycle and independent of it) can be determined by extrapolation^{6,7}). Using such an extrapolation and assuming heat shielding at still temperature only, a 5 ton aluminium bar would be subjected to about 1 mW heat leak. Here it was assumed that the heat leak is proportional to the exposed surface area; the likely cause of this is residual gas in the isolating vacuum. The volume- and mass-dependent heat leaks (such as ionizing cosmic-ray energy losses) appear to be much below this number. With existing refrigerators this heat leak can be absorbed at 0.05-0.1 K ^{6,7}).

- iii) The acoustic properties of Al 5056 below 1 K are the subject of measurements which will be undertaken in the near future. The refrigerator noise originating from the boiling of liquid helium in the still and from the flow of ³He must be suppressed and attenuated as much as possible in order not to excite the vibrational modes of the bar at detectable level. It appears clear that the refrigerator must be designed together with a proper suspension system.

In this work we address ourselves to the first problem by experimentally determining the thermal conductivity and the heat capacity of a sample of Al 5056. The desired refrigerator characteristics are discussed on the basis of the measured properties.

2. THERMAL CONDUCTIVITY

The cylindrical sample rod, with a larger cylinder at each end, was connected to a dilution refrigerator as shown in Fig. 1. A heater and a thermometer were fixed at each end.

The thermal conductivity of the sample was determined in the following way: a constant heating power $\dot{Q}_n$ was applied to the heater at the warm end of the test rod, of length ℓ and cross-sectional area A , while stabilizing the cold-end temperature T_0 by feedback to the heater of that end. As our temperature differences were rather large, we determine in this measurement the thermal conductivity integral

$$\int_{T_0}^{T_n} \kappa(T') dT' = (\dot{Q}_n + \dot{Q}_{\text{res}}) \ell / A \quad (1)$$

rather than the thermal conductivity itself. Here we assume that the distributed residual heat leak to the sample rod can be reduced to (and added with the leak of) the warm end, giving an effective heat leak $\dot{Q}_{\text{res}}$. With the additional assumption that $\dot{Q}_{\text{res}}$ is constant during the measurements (which was verified by repeating each series of measurements in opposite order), one can determine the thermal conductivity from the successive differences of heating powers $\dot{Q}_n$ and warm-end temperatures T_n :

$$\kappa(T_m)(T_{n+1} - T_n) = (\dot{Q}_{n+1} - \dot{Q}_n) \ell / A, \quad (2)$$

where $T_m \approx (T_{n+1} + T_n)/2$ for small differences of heating powers. The thermal conductivity data are plotted in Fig. 2. Other measurements on some AlMg alloys down to 4 K are also included^{8,9}).

The data for the normal state agree very well with the extrapolation of the measurements above 4 K for slightly more dilute alloys. The nearly linear temperature dependence shows that the electron conduction mechanism dominates. In the superconducting state the thermal conductivity approaches a T^3 line, characteristic of the phonon thermal conductivity. It would seem plausible that the phonon scattering by normal electrons suppresses the phonon conductivity near and above the critical temperature, so that the electron conductivity becomes dominant at 1 K.

The phonon specific heat (discussed in the next section) together with the measured phonon thermal conductivity determines the phonon mean free path, which will be compared with the grain size from metallographical observations.

3. SPECIFIC HEAT

The effective heat capacity C_{tot} of the warm end of the sample and then the specific heat c of the material were calculated from the thermal transient $T_n \rightarrow T_{n+1}$ determined by the relationship

$$\dot{Q}_{n+1} + \dot{Q}_{\text{res}} - C_{\text{tot}}(T) dT/dt = \int_{T_0}^T \kappa(T') dT' A / \ell . \quad (3)$$

This can be simplified by using the equilibrium thermal conductivity integral of Eq. (1):

$$C_{\text{tot}}(T_m) = [(\dot{Q}_{n+1} - \dot{Q}_n) / (T_{n+1} - T_n)] \tau_m ,$$

where $\tau_m = [(T_{n+1} - T) / (dT/dt)]_{\text{mean}}$ is the average time constant for the transient $T_n \rightarrow T_{n+1}$.

In our first run the warm-end heater was made of thin manganin wire, the heat capacity of which dominated that of the superconducting sample. In the second run this heater was replaced by a thin copper wire heater; the results (shown in Fig. 3) below 200 mK come from the second run only. The corrections due to addenda (heater, thermometer, Cu wires, and GE varnish) were below 1% for all data shown.

The normal-state specific heat of Fig. 3 agrees reasonably well with that of pure Al ¹⁰⁾ and is dominated by the electronic contribution. In superconducting state the number of normal electrons falls as $(T/T_c)^4$. In a pure superconductor this leads to a fast drop of the specific heat below T_c , ultimately revealing the phonon specific heat in the case of no trapped flux. In our sample the drop of the specific heat is much slower; the likely cause of this is the presence of various metallurgical phases with different zero-field critical temperatures. In all our zero-field measurements the external stray fields were compensated by a double μ -metal shield which, however, does not exclude small amounts of trapped flux.

In order to estimate the phonon contribution, let us assume that the Debye temperature θ_D of Al 5056 is 390 K, equal to that of pure Al. The characteristic phonon wavelength $\lambda = (\theta_D/T)d$, where d is equal to the lattice spacing, would then be 0.1 μm at 1 K and 1 μm at 0.1 K, which exceed all impurity distances by more than one order of magnitude. The majority of phonons are therefore not scattered by the impurity atoms. The phonon Debye specific heat would be $c_{V,\text{ph}} = 1.21 (T/1 \text{ K})^3 \mu\text{J g}^{-1} \text{ K}^{-1}$, which would give a phonon mean free path $\ell_{\text{ph}} = 3\kappa_{\text{ph}}(c_{\text{ph}}\rho v_s)^{-1} = 450 \mu\text{m}$ by using the measured phonon heat conductivity. The grain sizes, measured from microphotographs (see Fig. 4) taken of polished and etched samples of the same material, show the smallest dimensions varying from 200 to 50 μm ; the largest grain dimensions are about 400 μm . In view of the uncertainty of the Debye temperature for our alloy, the calculated phonon specific heat is consistent with the observed grain size and measured heat conductivity in the superconducting state. The measured specific heat below 0.3 K is at least two orders of magnitude higher, and must therefore represent residual electronic heat. This may be due to trapped flux or to a minority metallurgical phase which has a lower transition temperature.

From the above discussion we conclude that in the superconducting state the specific heat is given by the electronic system, but the heat is transported by long-wavelength phonons, which, unlike electrons, are not scattered by impurities. By extrapolating the measured specific heats to 50 mK, we may determine the thermal diffusivity $\alpha = \kappa/\rho c$ in our temperature range of interest. This is shown in Fig. 5 together with the estimated behaviour above 4 K.

Although it is known that in dilute Al alloys none of the alloying elements of Al 5056 are magnetic, it cannot *a priori* be excluded that a Mg-rich phase could be formed, where Mn or Cr would be paramagnetic. As we do not see any sign of a magnetic anomaly in our data, we may conclude that the amount of such phases is small.

4. CRITICAL TEMPERATURE

The critical temperature of our sample was determined by observing the midpoint of the inductance transient of a 10-turn coil wound around the warm end of our sample. The measurement was made at 10 kHz frequency; the width of the transition

is shown in Fig. 6 at various temperatures. The transition temperature as a function of field is given in Fig. 7; we find that its shape does not resemble a clean BCS curve, but is rather composed of two such curves, suggesting the presence of two metallurgical phases. We note that the zero-field critical temperature agrees quite well with the extrapolation of data on more dilute AlMg alloys¹¹).

5. CONCLUSIONS

Using the measured heat conductivity and diffusivity, we may compute the time dependence of the temperature of a 5 ton Al 5056 bar, after applying a thermal ground at $t = 0$ in the middle section. Figure 8 shows some such curves. In Fig. 9 the corresponding heat flux at the thermal ground is given. Clearly, in our fictitious example these heat fluxes are in excess of the cooling power of any refrigerator for a few minutes, simply meaning that in reality the cooling speed is limited by the refrigerator during an initial delay of some tens of minutes. The main delay, however, is nearly independent of the refrigeration power and is determined by the thermal diffusivity of the material. This becomes evident in Fig. 10, which shows the heat extraction rate versus warm-end temperature, compared with the cooling power of the refrigerator of Ref. 6. Our example shows that this material has a large enough diffusivity for cooling multiton bars of reasonable shape, but that the diffusivity and conductivity limit the cooling speed rather than the available refrigeration power.

In steady-state condition the thermal conductivity in the superconducting state sets a limit to the residual heat leak that can be tolerated on the bar. Figure 11 shows the temperature distribution along the bar for various values of the residual heat leak. Although the refrigerator of Ref. 6 can absorb a 1 mW heat leak below 0.1 K, the heat conductivity of the Al 5056 bar material limits the tolerable leak to an order of magnitude less, if the bar ends are to be kept below 0.1 K. The maximum temperature of 50 mK would require a heat leak below 10 μ W. Such low heat leaks can be obtained by heat shielding below the still temperature.

Multiple heat shields have some additional advantages in our application. First, they may provide intermediate masses for mechanical filters which are useful

for the acoustic isolation of the mixing chamber from the higher temperature stages. Secondly, the reduced heat leaks allow operation at much reduced ^3He mass flow, resulting in smaller boiling noise in the still and a lower level of acoustic emission due to flow in the heat exchangers. Thirdly, the lower helium temperature in the heat exchanger and mixer increases the sound attenuation of both dilute and concentrated solutions of ^3He and ^4He , providing better acoustic isolation through the columns of liquid.

The superconducting transition width and field dependence of the critical temperature suggest that the material may consist of several metallurgical phases. These pieces of information may be valuable in the elucidation of the acoustic properties of this material, the measurements of which are now under way.

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Figure captions

- Fig. 1 : Geometry of the sample rod, the cold end of which is fixed to the heat contact in the mixing chamber of a dilution refrigerator. The cold-end heater H_c is made of manganin wire and the warm-end heater H_w of 50 μ m Cu wire; both are bifilar wound. The coil for measuring the superconducting transition is made of 0.1 mm Cu-clad NbTi wire. T_c and T_w indicate the cold and warm resistance thermometers.
- Fig. 2 : The heat conductivity of Al 5056 below 1 K in zero (s) and 240 G (n) applied field. The inset shows the conductivity of two more dilute Al alloys above 4 K: Al 5052 (2.5% Mg, 0.25% Cr) and Al 5154 (3.5% Mg, 0.25% Cr).
- Fig. 3 : The specific heat of Al 5056 alloy below 1 K in zero (s) and 240 G (n) applied field. No data of other alloys exist for comparison.
- Fig. 4 : Al 5056 etched in HF for 30 minutes.
- Fig. 5 : Thermal diffusivity $\alpha = \kappa/\rho c$ of Al 5056 at zero (s) and 240 G (n) field below 1 K temperature (solid and dashed lines). The diffusivity above 4 K (dotted line, shown for comparison) is obtained by using the heat conductivity of Al 5154 (Ref. 9) and the specific heat of pure Al (Ref. 10), which is believed to be near that of dilute alloys.
- Fig. 6 : The inductance of a 10-turn coil around the warm end of the Al 5056 sample, as a function of the relative temperature T/T_c , at some representative field values. The frequency of measurement is 10 kHz. The open points correspond to warming and closed points to cooling of the sample.
- Fig. 7 : The critical temperature of Al 5056 as a function of magnetic field.
- Fig. 8 : Temperature distribution along a 3 m long, 5 ton Al 5056 bar after applying a 0.1 K thermal ground at the time $t = 0$ in the middle of the bar, which was initially at uniform 1 K temperature. The external heat leak to the bar is supposed to be negligible. The curves are numerical solutions of the non-linear heat equation.

- Fig. 9 : Heat extraction rate at the thermal ground for the example of Fig. 8.
- Fig. 10 : Heat extraction rate at the thermal ground as a function of the warm-end temperature (solid line), compared with the cooling powers of the dilution refrigerators of Ref. 6 (dashed line).
- Fig. 11 : Temperature distribution along half bar, in steady-state condition, for various values of the residual heat leak distributed on the lateral surface of the bar. The temperature T_0 at the heat sink in the middle section ($x = 0$) is taken as the temperature at which the refrigerator of Ref. 6 can absorb the indicated heat leak.

Fig. 1

Fig. 2

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Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 10

Fig. 11