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Low temperature thermal conductivity of aluminum alloy 5056

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ABSTRACT

The thermal conductivity of 5056 aluminum alloy was determined from 4.2 K to 120 K using a differential steady-state method. This method has been implemented in a low temperature cryostat using a Gifford–McMahon cryocooler as heat sink. The thermal conductivity of the 5056 H39 aluminum alloy was determined since it was under consideration as a part of a thermal link for the Planck research satellite. As expected, below 10 K the thermal conductivity is exclusively given by the electron-defect scattering term. At higher temperature, the other terms from the electronic and the lattice contributions come into play but the electronic thermal conductivity term is still dominant. A workable fit, based on theory, is presented and can be used up to 300 K. Our measurements are compared with data at lower temperature and available fits from the literature.

1. Introduction

In aerospace or physics applications, low mass density materials with high thermal conductivities such as aluminum alloys are used to construct thermal links or structures with a good thermal conductivity. There are several aluminum alloys that undergo different thermal and mechanical treatments depending on the applications. The Al 5056 alloy belongs to the 5000 series which are alloyed with magnesium. It contains 5.2% of magnesium, 0.1% of Mn, 0.1% of Cr by weight and some other impurities. This alloy was considered as a good conductor and structural material in the construction of the Planck telescope among other aluminum alloys [1]. Here, we present thermal conductivity of the alloy Al 5056 H39 at a higher temperature range from 4.2 K to 120 K using a steady state differential method. H39 denominates strain hardening and stabilizing by low temperature heating giving a high degree of hardness. Our measurements are compared with the thermal conductivity data reported by Coccia and Niinikoski for an Al 5056 between 0.05 and 1.3 K [2]. To the best of our knowledge, our data are the sole thermal conductivity data reported in the literature for this alloy above 4 K. A workable fit, based on theory, is presented and can be used up to 300 K.

2. Determination procedure and experimental set-up description

2.1. Differential method

We measured the thermal conductivity with a 1D steady-state differential method, for which the relationship between the heat flux and the temperature gradient is given by the Fourier law $\vec{q} = -k(T)\vec{\nabla}T$ where q is the heat flux density and $k(T)$ the thermal conductivity; a function of temperature. When the cross-sectional area of the domain is constant, the integration of the Fourier law gives by definition the average value of the thermal conductivity $\overline{k(T)}$

$$\overline{k(T)} = \frac{1}{T_h - T_c}\int_{Tc}^{Th} k(T)\,dT = \frac{Q}{T_h - T_c}\frac{l}{S}, \tag{1}$$

where Q is the heat flux dissipated across the sample, S the cross-sectional area, l the distance between the cold (T_c) and hot (T_h) temperature measurement locations. Eq. (1) defines the average value of the thermal conductivity within the temperature range of measurement but for simplicity we assume that it is equivalent to the thermal conductivity at the average temperature of the measurement range, i.e. $\overline{T} = (T_h + T_c)/2$. This assumption introduces a systematic error, $\overline{k(T)} - k(\overline{T})$, which is small for $T_c \approx T_h$ and even vanishes when $T_c \to T_h$. In our measurements we imposed $\Delta T = T_h - T_c$ around 0.05–0.3 K, sufficiently small to neglect the systematic error introduced by the average value simplification.

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2.2. Experimental set-up and procedure

The experimental set up is based on a vertically oriented vacuum can cryostat with a Gifford–McMahon cryoccooler serving as cold source and located on the top flange. The second stage of the cryocooler has the capability of maintaining 4.2 K under a heat load of 1.5 W. The samples are thin tapes clamped between two high-purity copper blocks with copper-charged grease as described in [3]. Each copper block is instrumented with a calibrated Cernox 1050 temperature sensor, mounted also with copper-charged grease in small cavities. The upper cooper block is associated with the measurement of T_c and the lower one with T_h as described in Fig. 1. The lower copper block is heated to T_h with a Manganin® wire heater (referred as the Q-heater) wound around it while the upper copper block is maintained at T_c. The measurement part of the rig, i.e. the two copper blocks and the sample, is surrounded by a high purity copper radiation shield. The copper shield is 3 mm thick to ensure a constant temperature over the entire volume. The copper shield is separated from the second stage of the cryocooler by a stainless steel weak thermal leak and a heater (see Fig. 1). The purpose of this thermal link is control the T_c temperature over a large temperature range with a reasonable power input dissipated on the second stage of the cryocooler. This thermal leak was designed to have a 300 K temperature different across it while dissipating 12 W. The copper shield is further surrounded by an aluminum radiation shield, thermally anchored at the first stage. Both radiation shields have a superinsulation blankets located on their exterior.

While T_c is maintained at a constant value by the mean of the thermal link heater, the power through the Q-heater is controlled to generate the temperature difference across the sample, ΔT. Repeated measurements were made at different T_c values with ΔT varying between 0.05 and 0.3 K. The data were recorded when the value of both temperatures become stable within a mK. The temperature stabilization can take several minutes at low temperature and up to an hour or longer at higher temperatures.

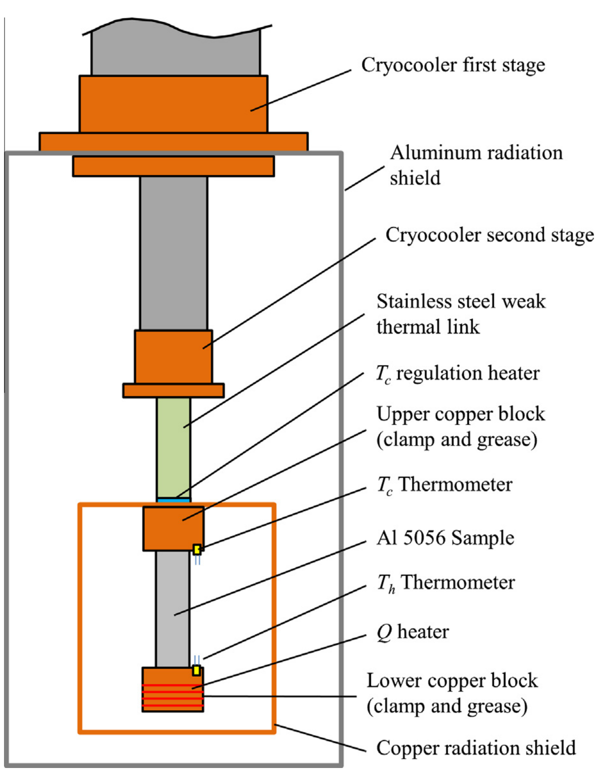

Fig. 1. Schematic of the measurement part of the thermal conductivity rig.

To reduce surface contaminations, the sample was stored in a vacuum packaging before the measurement. The electron mean free path in Al alloy, 0.06 μm at 4 K, is much smaller than the smallest dimension of the samples. Thus there is no 2D effect on the electron scattering and our results are therefore applicable to bulk samples of this material.

2.3. Experimental errors

The dimensions of the sample were measured at room temperature and their values at low temperature are estimated from the thermal contraction data [4]. Table 1 gathers the sample dimensions and their precision. The uncertainties in thermal contraction data are around 10% and the thermal contraction of aluminum alloy is at most 0.5% in the temperature range of the experiment. Thus the uncertainty induced by the thermal contraction is negligible compared to that incurred in the determination of the dimension of the sample (7% for the thickness).

The two Cernox® sensors were calibrated by Lakeshore Cryotronics. The error in the temperature measurement ranges from 2 mK at 4 K to 10 mK at 120 K due to the difference between the calibration fit and the data and the electronic chain. We also considered the systematic error in the temperature measurements due to the thermal resistance between the copper blocks and the grease. This error is neglected in the rest of the error analysis since previous calculations estimated that the extra temperature difference created by this thermal resistance is small compare to the ΔT across the sample [1].

The total heat flux, Q, ranged from 5 to 500 μW, is generated and monitored by a Keithley 2400 sourcemeter and the uncertainty is at most 0.5% of the value. Q is obtained with a 4-wire measurement and calculated from the current generated by the sourcemeter and the measurement of the voltage across the resistance.

The typical relative measurement error value of the parameters constituting Eq. (1) are gathered in Table 2. The main contribution to the thermal conductivity uncertainty is the temperature measurement uncertainty and that of the sample thickness.

Conduction through the instrumentation wiring and radiation heat losses must be examined as well as they can constitute systematic errors. From room temperature to the copper radiation shield, all the wires are PTFE insulated twisted pair OFHC cooper wire with an AWG of 30. The wires are thermally anchored onto the two radiation shields (aluminum and copper). From the copper radiation shield, several other wires are used. For the heater, a Constantan® twisted pair of 0.2 mm in diameter wire is used for the voltage measurement and a twisted pair Manganin® wire of 0.65 mm diameter for the current. Both wires are 1 m long. For both thermometers, the wiring is composed of 2-m long twisted pair of 0.152 mm diameter Ph–Br wires. All wires, within the copper radiation shield, are installed in a pig tail manner (i.e. as spring) to avoid any contact with the cooper shield. The wiring of the T_c sensor is thermally anchored to the copper shield and as the copper shield temperature is regulated at T_c or very close, the heat losses through the T_c sensor wiring are considered negligible. The maximum value of the conductive heat load on the sample is around 0.8 μW for a temperature of 22 K. The conductive heat load is two to four orders of magnitude lower than Q and therefore will be neglected in the error analysis.

Table 1
Dimensions of the sample at 300 K.

Length, l (mm)	52.00 ± 0.05
Height, h (mm)	10.30 ± 0.05
Thickness, e (mm)	0.074 ± 0.002