

Use of Strain Gages for Low Temperature Thermal Expansion Measurements

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The use of strain gages for low temperature thermal expansion measurements is increasing, due to its convenience, and relative accuracy. The determination of thermal expansion with strain gages is complicated by "thermal output strain", a phenomena caused by the temperature dependence of the gage. If thermal output strain is properly compensated, strain gages may be used to measure thermal expansion in much the same manner they are used to measure applied strain. An algebraic method to compensate strain gage thermal output over the temperature range 300 K to 4 K is reported here. The results of the thermal expansion tests on two structural alloys and two superconductors are also reported.

INTRODUCTION

Generally, the thermal expansion of solids is measured using a "dilatometer", an instrument which works on the ability to detect the differential expansion between the test material and a low expansion reference material. The method of using strain gages for thermal expansion measurement [1] also relies on the use of a reference material with known expansion. It is attractive because it allows rapid and accurate determination of expansion properties of a broad range of material classes. Another advantage is the capability to test various specimen geometries that cannot be accommodated with other techniques. Applications of strain gages for expansion measurements have been reported to be viable over a range of temperatures on various materials [2 - 4]. Although this technique is applicable to measuring thermal expansion down to liquid helium temperature (4 K), little or no information has been reported.

Research on strain gages available for use at cryogenic temperature, has shown that gages made with a Ni-Cr alloy conductor have the best gage-to-gage reproducibility [5]. Although this characteristic is favorable for their use in thermal expansion tests, the electrical resistance versus temperature characteristics of Ni-Cr alloys shows a slope inversion at around 20 K that is unfavorable. This slope inversion coupled with a tendency for gage self-heating in this temperature regime, necessitates the careful gage characterization that is detailed here.

PRINCIPLE OF THE MEASUREMENT METHOD

When a strain gage is mounted on a stress-free specimen, and the temperature of the specimen is changed, the resistance of the strain gage changes. The change in the electrical output of the gage is referred to as "thermal output strain" (TOS) and is caused by a combination of the

specimen's expansion and the strain gage's temperature dependence. If the TOS is compensated correctly, strain gages can be used to measure thermal expansion.

The technique for compensating the measurement error requires using strain gages from the same manufacturing lot to ensure they are as close to identical as possible. Traditionally this compensation has been done electrically, using the canceling characteristics of the wheatstone bridge on a dummy "identical" gage on a reference specimen. There are drawbacks; the dummy specimen must be measured along with the test specimen and kept at the same temperature. In addition if there are problems with the dummy gage, the data will not be recoverable.

Another method, used here, is to algebraically compensate the TOS data. The strain gage lot is characterized by individually testing a few strain gages from the lot on a reference material with known thermal expansion. The mathematical difference between the reference specimen's expansion at a particular temperature and the TOS signal at the same temperature, is the error that prevents measuring thermal expansion directly. The magnitude of the error is temperature dependent and must be characterized as a function of temperature. The magnitude of the error is independent of the material to which the strain gage is bonded and can be thought of as the electrical output that the gage would have if it were bonded to an "ideal reference material" having zero expansion or contraction. This measurement error data can then be used to algebraically compensate TOS data on a material of interest to obtain its thermal expansion.

TEST MATERIALS

Two alloys, AISI 316LN and 2024-T4 Al are measured and compared to published data. The samples are in plate form, 40 mm square by 10 mm thick.

Two low temperature, superconductor materials are also tested. They are composite wire samples of Copper/ NbTi and Copper/ Nb₃Sn. The Copper/ NbTi wire has a 3.6 : 1 copper to NbTi ratio. The Copper/ Nb₃Sn wire composition is ; 0.41 Cu, 0.03 Nb, 0.42 CuSn, 0.14 Nb₃Sn. The samples are 50 mm long, having a rectangular cross-section of 1 mm by 2 mm.

Commercially pure copper, also referred to as oxygen-free high-conductivity (OFHC) copper, with copper content $\geq 99.95\%$, is used as the reference material with a known thermal expansion [5].

EXPERIMENTAL METHOD

Commercially available, foil-type, resistance strain gages from the same manufacturing lot are used. The strain gages are made from Ni-Cr alloy and have 350 Ω resistance. Two different gage types (from two different lots) are used because a thin gage width is needed for the more difficult application on the superconductor wires. The adhesive used is a two component epoxy (M-Bond AE-15) suitable for cryogenic use. A commercial strain indicator system is used that has an estimated accuracy of ± 1 microstrain.

Specimen temperature is controlled in a vacuum-insulated stainless-steel dewar. The temperature measuring system uses a silicon diode temperature sensor and has an estimated

accuracy of ± 0.5 K. Thermally conductive grease is used to ensure thermal contact of the sensor to the specimen.

The active strain gage is wired to the strain conditioner using a quarter bridge configuration with a three lead wire connection. The excitation voltage is low (0.5 Vdc) to avoid gage self-heating that can occur due to the power density at the gage [6]. The room temperature gage factor, supplied by the gage manufacturer is used throughout.

Tests are conducted by thermal cycling the test specimen (the material of interest or the reference material) from room temperature (293 K) to liquid helium temperature (4 K). The strain indicator output is balanced at 293 K to give a zero strain readout. The test specimen is cycled from 293 K to 4 K to establish confidence in the response of the gage and associated instrumentation, i.e.: the strain gage signal returns to zero at 293 K. Data is obtained while the specimen is slowly cooled in a dewar. The specimen is cooled down to 77 K using liquid nitrogen and on to 4 K with liquid helium. A reversal of this scheme is used to obtain data on the warm-up cycle.

The characterization of the strain gage lot is done by testing "identical" gages from within the lot on the reference expansion material (OFHC copper). The strain gage error (the difference between TOS and the actual copper expansion) is calculated and plotted as a continuous curve, over the temperature range, and then curve fit with a polynomial expression. The descriptive equation is used for compensation of the TOS data taken in thermal expansion tests.

RESULTS

A summary of the test results is found in Table 1. The estimated accuracy of the values are ± 5 %, based on the characterization of the strain gage lot with the OFHC copper reference material. Correction for the temperature dependence of the gage factor, not done here, can further refine the accuracy (~ 2 %). Figure 1 shows a graph of the TOS data for the aluminum alloy along the thermal expansion curve that is obtained by mathematical correction of the TOS. This is a graphical representation of the strain gage error. Figure 2 shows test results along with published data [7] for aluminum alloys.

CONCLUSIONS

The characterization of "identical" gages from the same strain gage lot is necessary for converting TOS data to thermal expansion data. This is the by far the largest source of error and, it's compensation could be sufficient depending on the accuracy desired.

Special attention should be given to the potential for gage self-heating which may not be excessive enough to cause noisy data but could cause a subtle data shift, that is reproducible [6] and could lead to misinterpretation of the data.

Temperature measurement is critical to the accuracy of these measurements. Taking sufficient data, over a number of thermal cycles, to obtain good agreement will help assure that thermal equilibrium conditions are achieved.

Table 1. Thermal Expansion Test Results

TEMP (K)	THERMAL EXPANSION (%)			
	2024 T4 Al	316LN SS	Cu/ NbTi	Cu/ Nb3Sn
77	-0.38	-0.28	-0.28	-0.25
4	-0.41	-0.29	-0.31	-0.29

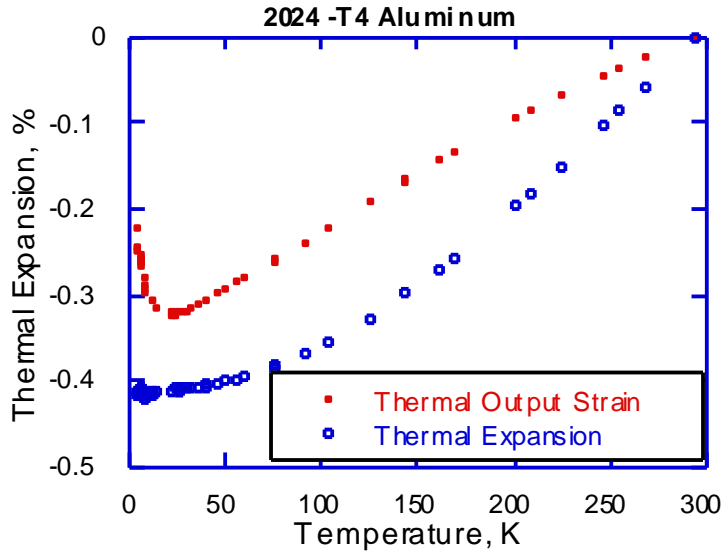


Figure 1. TOS and Compensated Data.

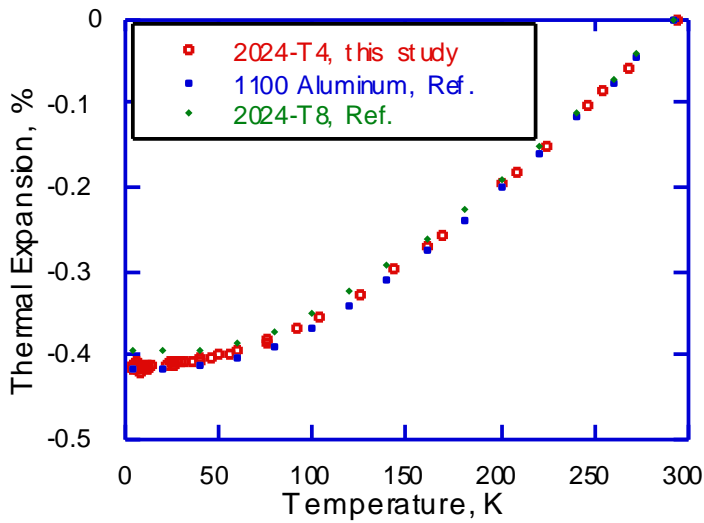


Figure 2. Comparison with literature.

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