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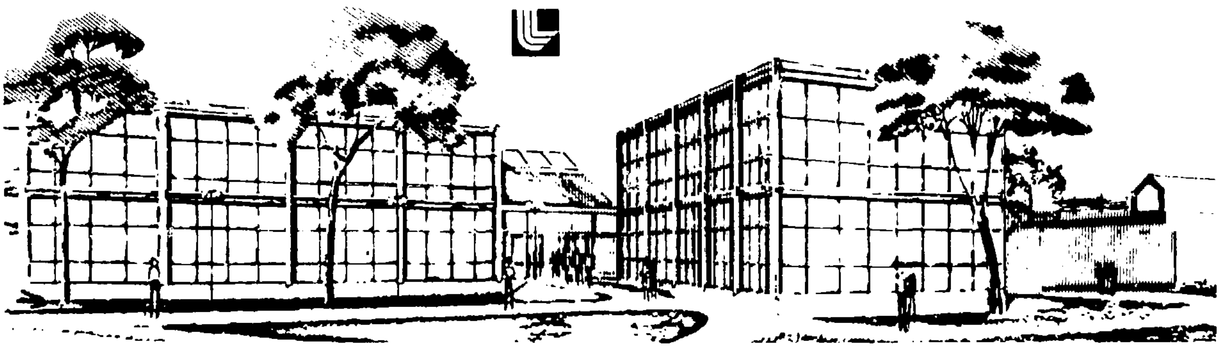

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EVALUATION OF METAL-FOIL STRAIN GAGES FOR CRYOGENIC APPLICATION IN MAGNETIC FIELDS

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INTRODUCTION

The requirement for the design and construction of large superconducting magnet systems for fusion research has raised a number of new questions regarding the properties of composite superconducting conductors. One of these, the effect of mechanical stress on the current-carrying capacity of Nb_3Sn, is of major importance in determining the feasibility of constructing large magnets with this material. A typical experiment for determining such data involves the measurement of critical current versus magnetic field while the conductor is being mechanically strained to various degrees. Techniques are well developed for the current and field measurements, but much less so for the accurate measurement of strain at liquid-helium temperature in a high magnetic field. For this reason, we have undertaken a study of commercial, metal-foil strain gages for use under these conditions. The information developed can also be applied to the use of strain gages as diagnostic tools in superconducting magnets.

EXPERIMENTAL TECHNIQUES AND RESULTS

At the start of this study, we decided that the following should be investigated:

- Thermal zeroshift (apparent strain) due to the mismatch between the strain gage and substrate expansion coefficients for different gage compositions and typical substrate materials.
- Limitations on gage excitation power for both pulsed and continuous excitation.
- Temperature dependence of the gage factor.
- Magnetic field effects up to 12 T.

After reviewing existing information [1-13] on the use of strain gages under conditions similar to those of interest here, we decided that strain gages using nickel-chromium (modified Karma*) strain-sensing foils were most applicable. Therefore, for all tests we used glass-fiber-reinforced, epoxy-phenolic-resin-backed strain gages with modified Karma strain-sensing foil (WK). We tested Micro-Measurements, Inc., WK-XX-125AD-350 and WK-XX-250BG-350 strain gages. The 125AD grid is 3.18 mm square; the 250BG grid is 6.35 mm long and 3.18 mm wide and has twice the grid area of the 125AD. The strain gages were bonded with Micro-Measurements M-Bond 600 adhesive, cured for 2 h at 93°C. For all tests, the strain gages were wired into single-active-arm, equal-arm bridges using three-wire compensation for variation of lead-wire resistance with temperature.

*Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Energy Research and Development Administration to the exclusion of others that may be suitable.

Thermal-Zeroshift (Apparent-Strain) Tests

For tests of thermal zeroshift (apparent strain) versus temperature, we mounted WK-XX-125AD-350 strain gages having compensations (XX) of 6, 9, 13, and 15 ppm/°F on each of the following materials: 316 stainless steel (SS), 21-6-9 SS, OFHC Cu, a Nb_3Sn multifilament conductor, and a NbTi multifilament conductor. On the back of each sample, we also mounted a Micro-Measurements, Inc. CLTS temperature sensor.

The samples were run four at a time, with repeat data taken on three in a second run. For any set of four samples, we needed to record 20 channels of data, i.e., data from 16 gages and 4 temperature sensors. To do this conveniently, we used a small, computer-controlled data acquisition system capable of handling 100 channels with a scan rate of 10 channels per second. This system powers the channels sequentially with pulsed constant current and uses an integrating digital voltmeter to measure the output voltage without amplification. The data are recorded on digital magnetic tape and then computer analyzed and plotted from this tape.

The samples were hung on a rod at the top of a helium cryostat that contained a small amount of helium in the bottom. By slowly lowering and raising the samples, we could obtain a complete set of data from room temperature to 4.2 K and back.

The curves in Fig. 1 show the thermal zeroshifts for four gages that were mounted on OFHC copper. The data for the other four samples are similar, but are shifted up or down slightly according to the expansion coefficient of the substrate material.

Three interesting test results are shown in this figure:

- The best compensation from room ambient temperature to 4.2 K is 13 ppm/°F; this was true for all sample materials tested.

- There is a sharp reversal in the apparent-strain curve near 20 K, similar to that measured by Telinde [3,5,6].
- The slope of the apparent-strain curve is very large at 4.2 K, indicating that operation at uniform temperature is essential to accurate measurements.

Figure 2 shows the apparent-strain curve expanded near 4.2 K for a WK-15-125AD-350 strain gage with a 15-ppm/°F [illegible]ation bonded to the 2024-T3 aluminum beam used for gage [illegible] measurements. For the 1-K interval between 4 [illegible], the apparent strain is approximately −150 μm/m. For this same gage bonded to OFHC copper, the corresponding apparent strain is about −210 μm/m.

Self-Heating Tests

We performed a number of tests to measure self-heating [illegible] in gages having 15-ppm/°F compensation. Our purpose was to determine operating conditions under which we could obtain reproducible, accurate data at maximum sensitivity.

For these tests, bridge excitation was either pulsed constant current (40 ms on, 10 s off) or continuous constant current. Strain-gage current was varied so that the dissipation levels for strain-gage grid power ranged from 1 to 300 mW/cm² during the time that the current was on. The gages were tested both in direct contact with [illegible] and with a coating of Dow Corning High Vacuum Grease [illegible], No. [illegible] (silicone) to limit heat transfer from the exposed surface.

Four 15 ppm/°F compensation WK-15-125AD-350 strain gages of the same lot number were tested. All four were bonded to the 2024-T3 aluminum beam used for gage factor measurements. The beam was oriented with the plane of the gages vertical to prevent helium bubbles from being entrapped over the gage grids. None of the tested strain gages zeroshifted permanently during any of the self-heating tests.

Figure 3 shows the self-heating zeroshifts for one of the 125AD strain gages for various strain-gage currents under four different test conditions:

- Pulsed constant current without any protective coating,
- Pulsed constant current with a protective coating of silicone grease,
- Continuous constant current without protective coating, and
- Continuous constant current with a protective coating of silicone grease.

The strain-gage current ranged from 0.13 mA (0.06 mW/cm^2) to 5 mA (88 mW/cm^2) for continuous constant current and to 10 mA (350 mW/cm^2) for pulsed constant current. The plotted data are referenced to a 1-mA strain-gage current.

The results shown in Fig. 3 are typical of those obtained during this series of tests. The following observations can be made:

- For pulsed constant currents to 10 mA (350 mW/cm^2) in the 125AD strain gage, there is *no significant difference* in the self-heating zeroshifts observed with and without a coating of silicone grease on the gage.
- *For strain-gage currents to 3.5 mA (43 mW/cm^2), the self-heating* zeroshift is nearly independent of whether the strain-gage current is pulsed or continuous or whether the gage is or is not coated with silicone grease.

Two WK-15-250BG-350 strain gages of the same lot number were also tested for various strain-gage currents ranging from 0.25 mA (0.11 mW/cm^2) to 25 mA (1093 mW/cm^2). No protective coating was used.

Figure 4 illustrates the self-heating zeroshifts for one of the two gages; the data are representative of both gages:

- For strain-gage currents less than 15 mA (96 mW/cm^2), there is no significant difference between the self-heating zeroshifts observed for the pulsed and continuous constant currents.
- For currents greater than 15 mA, the self-heating zeroshifts for the pulsed and continuous constant currents begin to diverge, indicating an increased temperature rise during continuous constant-current excitation.

Figure 5 shows the self-heating zeroshifts from Figs. 3 and 4 plotted against power dissipation in the strain-gage grid during the time that the current is on. The data are for pulsed constant-current excitation without any protective coating. There is reasonably good agreement between the data from the 125AD and 250BG strain gages, considering the differences in the grids and the fact that the gages were manufactured from different lots of strain-sensitive foil.

The data in Fig. 5 indicate that the self-heating zeroshift tends towards a single broad curve as a function of grid-power dissipation. This curve will be useful for preliminary circuit design in future applications where smaller strain gages might be needed.

Selection of the Optimum Strain-Gage Grid-Power Dissipation

Most of our early evaluations had been performed on the WK-15-125AD-350 strain gage. Subsequently, however, we selected the WK-15-250BG-350 strain gage as the optimum-size gage for all our anticipated testing requirements. There were two reasons for this choice: the 250BG is the largest strain gage that just fits our superconductor tensile-test samples, and it has twice the grid area of the 125AD. Therefore, a special lot (DG-K09FG14) of modified Karma foil with 15-ppm/°F compensation was purchased and put on reserve at Micro-Measurements in sufficient quantity to make about 1300 250BG strain gages. We standardized on one strain-gage pattern and one lot of material to reduce the number of variables that could influence strain measurements in high magnetic fields at 4.2 K.

Table I lists the information used in the selection of the gage operating current of 5 mA for the 250BG configuration. For comparison, this information is also given for the 125AD configuration. Note that for pulsed constant current, the grid-power dissipation is 44 mW/cm^2 only during the 40-ms on-time.

Our reasons for selecting this 44 mW/cm^2 power dissipation for the 250BG gage were:

- 5 mA to the strain gage is an easy number to remember.
- The power dissipation is consistent with Walstrom's 10 mW/cm^2 [Ref. 8], and Bower's 44 mW/cm^2 [Ref. 7], both obtained for continuous constant current.
- The self-heating zeroshifts are the same for pulsed and continuous constant current.
- The self-heating zeroshift of −90 $\mu m/m$ has proved to be very stable and repeatable in our tests.
- The output voltage from an equal arm bridge is about 1.88 μV per $\mu m/m$. The corresponding output voltage from a 10:1 asymmetric bridge is about 3.42 μV per $\mu m/m$. These output voltages are relatively high and ensure a good signal-to-noise ratio in most applications.

- Standard portable constant-voltage excitation strain indicators such as the BLH model 120 can be used without exceeding 44 mW/cm^2 in the strain gage. Such strain indicators are particularly useful for checkout, for troubleshooting, and for fast measurements of a few channels of data.

Preliminary Gage Factor Data

For measuring the temperature dependence of the gage factor, we bonded the gages to an aluminum flexure that was first strained to a selected value in bending through the use of supports of various diameter and then was temperature cycled. Since the strain in the flexure remains constant at all temperatures, the gage factor can be computed from the temperature-dependent output voltages. To compensate for apparent strain effects, we first determined this quantity in a temperature cycle with zero applied strain.

We constructed this constant-strain apparatus in a manner similar to that described by Telinde [3]. To minimize differential contraction effects, the aluminum flexure and the side supports were all cut from the same 2024-T3 aluminum plate with the same orientation. The fixture is shown disassembled in Fig. 6 and assembled in Fig. 7.

At this writing, the data for gage factor variation with temperature are still being processed. So far, however, we have used the apparatus to test WK-[illegible], Lot No. [illegible], strain gages in both tension and compression at applied strains of 1000 μm/m. The measured gage factors at 4.2 K for four gages in tension were 4.7, 4.9, 5.1, and 5.3% higher than the manufacturer's listed gage factor of 2.[illegible] at ambient temperature. For two gages in compression, the measured gage factors were 4.[illegible] and 5.[illegible]% higher than the ambient gage factor.

We estimate the error band for these results to be about ±0.4. For example, a measured gage factor that is 5% higher at 4.2 K than at ambient temperature could have a true value anywhere in the range from +4.6 to +5.4%. This corresponds to an error of ±4 μm/m in strain measurement at 1000 μm/m. For comparison, the manufacturer's gage factor at ambient temperature is quoted to an inaccuracy of 1%, which corresponds to a ±10-μm/m error in strain measurement at 1000 μm/m.

WORK IN PROGRESS

The following tasks are currently underway or will begin shortly:

- Measurement of gage factor variation with temperature for the WK-15-250BG-350 strain gages.
- Measurement of magnetoresistance to 12 T for the same gages. For this experiment, we shall mount gages in the three orthogonal directions to the magnetic field on a bar that can be strained at 4.2 K while it is in the magnetic field. We shall use an existing, operational tensile-test apparatus designed for measuring strain degradation of critical-current Nb_3Sn conductors. In this manner, we can measure the magnetic field effect as a function of field-gage orientation and background strain level.
- Evaluation of tough protective coatings that are not greases.
- Evaluation of other strain gages that might have desirable characteristics at 4.2 K, e.g., lower magnetoresistance, flatter apparent-strain curve near 4.2 K, or perhaps both.

SUMMARY

We have completed the following work related to evaluating and certifying strain gages for use in liquid helium at high magnetic fields:

- Apparent-strain tests to select optimum self-temperature compensation.
- Self-heating zeroshift tests using pulsed and continuous constant current with and without a protective coating of silicone grease.
- Selection of a standard strain gage for all anticipated future applications (WK-15-250BG-350, lot No. DG-K09FC14).
- Purchase and reservation of a large lot of modified Karma strain-sensitive foil of 15-ppm/°F compensation.
- Selection of an optimum strain-gage power dissipation and strain-gage current to allow a high degree of flexibility in selecting pulsed or continuous constant-current instrumentation or constant-voltage strain indicators.
- Preliminary measurements of gage factors at 4.2 K measured at 1000 μm/m in tension and compression.

ACKNOWLEDGMENT

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Table I. Information Relevant to the Selection of Strain-Gage Current for 4.2 K Operation

Characteristic	Strain gage WK-15-125AD-350	Strain gage WK-15-250BG-350
Strain-gage current (pulsed or continuous), mA	3.5	5.0
Grid area, cm^2	0.1	0.2
Power dissipation in grid, mW/cm^2	43	44
Nominal self-heating zeroshift relative to 1-mA strain-gage current (2024-T3 aluminum beam), μm/m	-75	-90
Bridge output with constant current excitation at 1000-μm/m strain (GF = 2.15), μV		
• Equal-arm bridge	1316	1880
• 10:1 asymmetric bridge	2394	3420

FIGURE CAPTIONS

Fig. 1. Thermal zeroshift (apparent strain) for WK-XX-125AD-350 strain gages on OFHC copper sample for self-temperature compensation XX = 06, 09, 13, and 15.

Fig. 2. Thermal zeroshift (apparent strain) in expanded scale near 4.2 K for WK-15-125AD-350 strain gage on 2024-T3 aluminum beam.

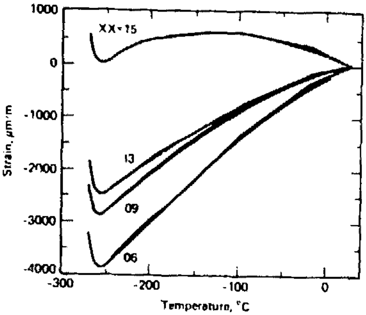
Fig. 3. Self-heating zeroshifts versus strain-gage current for one WK-15-125AD-350 strain gage for pulsed and continuous constant-current bridge excitation, with and without a protective coating of silicone grease. All data are referenced to 1 mA.

Fig. 4. Comparison of self-heating zeroshifts for pulsed and continuous constant-current bridge excitation versus current through one WK-15-250BG-350 strain gage having no protective coating. All data are referenced to 1 mA.

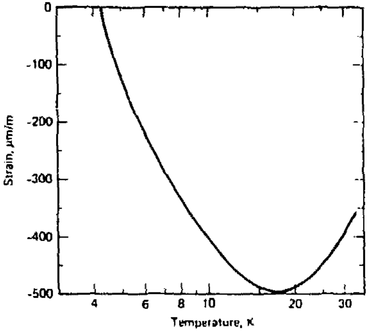
Fig. 5. Comparison of self-heating zeroshifts for two strain gages with different grid areas and no coating, versus power dissipation in grid, for pulsed constant-current bridge excitation. All data are referenced to 1-mA strain-gage current.

Fig. 6. Gage factor test fixture (disassembled).

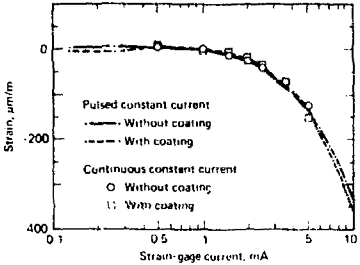
Fig. 7. Gage factor test fixture (assembled).



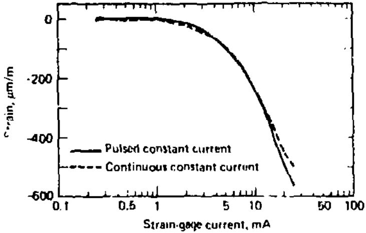
Freynik - Fig. 1



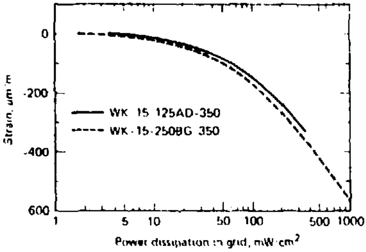
Freynik - Fig. 2


Strain, μm/m
0
-200
400
Pulsed constant current
Without coating
With coating
Continuous constant current
Without coating
With coating
0 1
0 5
1
5
10
Strain-gage current, mA

[illegible] - Fig. [illegible]

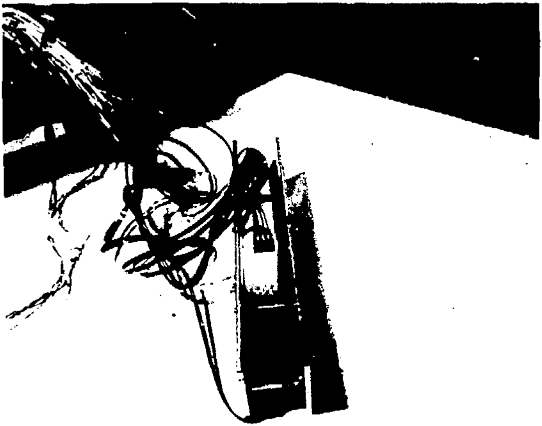


Freynik - Fig. 4



Freynik Fig. 5

Freynik - Fig. 6



[illegible]