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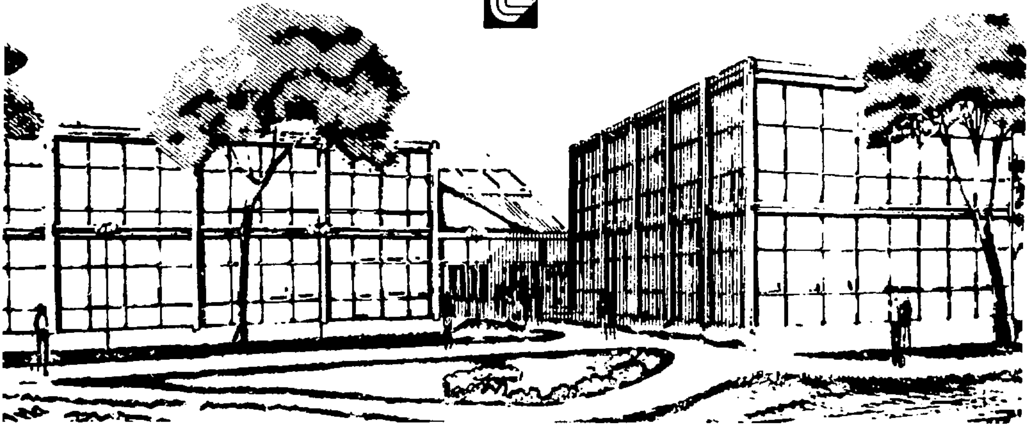

NICKEL-CHROMIUM STRAIN GAGES FOR CRYOGENIC STRESS ANALYSIS OF SUPERCONDUCTING STRUCTURES IN HIGH MAGNETIC FIELDS[*]

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Summary

We performed evaluation and calibration measurements on commercial nickel-chromium metal-foil strain gages in a high-magnetic-field (12 T), liquid-helium (4.2 K) environment. Our purpose was to fully characterize strain gages for use at cryogenic temperatures in high magnetic fields. In this study, we measured the magnetoresistance of a number of strain gages in three orthogonal directions at mechanical strain levels to 8900 μm/m. As a result, we defined a unique calibration curve for magnetoresistance strain errors that is independent of strain level and field direction to 12 T at 4.2 K. A current strain-gage application of ours is the measurement of superconductor mechanical properties. We will soon use these gages in the stress analysis of superconducting fusion magnets during cooldown from ambient temperatures and during operation at 4.2 K with magnetic fields to 12 T.

Introduction

The design and construction of large superconducting magnet systems for fusion research requires the measurement of thermal stresses during cooldown and of strains due to magnetic loads at 4.2 K. Strains must be accurately measured in the following applications:

- Tensile tests of superconductors to 10,000 μm/m at 4.2 K and magnetic fields to 12 T.
- Stress analysis on magnets to ±1000 μm/m during cooldown to 4.2 K without magnetic fields.
- Stress analysis on magnets to ±3000 μm/m at 4.2 K and magnetic fields to 12 T.

To date, published information has been inadequate to make valid and reliable strain measurements for the above applications. References one through seven discuss prior work at cryogenic temperatures without magnetic fields. References 8 through 15 discuss prior work at cryogenic temperatures with magnetic fields.

We began and are continuing a comprehensive study of strain gages for the above applications. The first portion of this research was reported at the Cryogenic Engineering Conference in August 1977.[16] The specific results reported at that time follow:

- The Micro-Measurements WK-15 strain gage[†] provided the flattest thermal zeroshift (apparent strain) curve between ambient temperature and 4.2 K for Nb_3Sn multifilament conductors, NbTi multifilament conductors, 316 stainless steel, 21-6-9 stainless steel, and OFHC copper when compared with WK-06, WK-09, and WK-13 strain gages.
- We selected a standard strain gage, Micro-Measurements WK-15-250BG-350, for all future applications. This is a glass-fiber-reinforced, epoxy-phenolic-resin-backed strain gage with a modified Karma (nickel-chromium) strain sensing foil.
- A special lot of K-15 foil (Lot No. DG-K09FG14) was placed on reserve at Micro-Measurements to provide about 1300 strain gages of the 250BG pattern. We did this to reduce the number of variables that could influence cryogenic strain measurements in high magnetic fields.
- We measured self-heating zeroshifts at 4.2 K for both continuous and pulsed constant current (40 ms on, 10 s off) bridge supplies. Grid-power dissipation was varied from 1 to 1000 mW/cm^2 during the time current was on. We selected a strain gage current to the 250BG strain gage of 5 mA (44 mW/cm^2) for all future tests. For this power dissipation, there is no significant difference between zeroshifts for continuous and pulsed constant current.
- The gage factor at 4.2 K was measured to be 5% higher at 4.2 K than at ambient for the WK-15-250BG-350 strain gage for both tension and compression. This data is an average of four gages in tension and two gages in compression to 1000 μm/m. The spread in gage factor ranged from +4.7 to +5.3%.

The second part of our research focused on strain gage magnetoresistance, which is the change in strain gage resistance produced by a magnetic field. To correct strain gage data for this effect, we measured the magnitude and variation of the magnetoresistance for the following conditions:

- A significant number of strain gages.
- DC magnetic fields to 12 T.
- Three orthogonal field directions.
- Increasing and decreasing fields.
- A wide range of strain levels.
- Liquid-helium temperature, 4.2 K.

These magnetoresistance measurements will be discussed in this paper.

Experimental Apparatus to Measure Strain Gage Magnetoresistance

A 6.35-mm-sq bar of ETP copper was cut to a 0.71-m length. We installed eight strain gages at the center of the bar, two on each of the four sides of the bar (Fig. 1). The strain gages were Micro-Measurements WK-15-250BG-350, Lot No. DG-K09FG14, with a 2.15 gage factor at 297 K and a 2.26 gage factor at 4.2 K.

The gages were bonded with M-Bond 600 adhesive and cured two h at 366 K (93°C). No protective

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[†] 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.

EHB

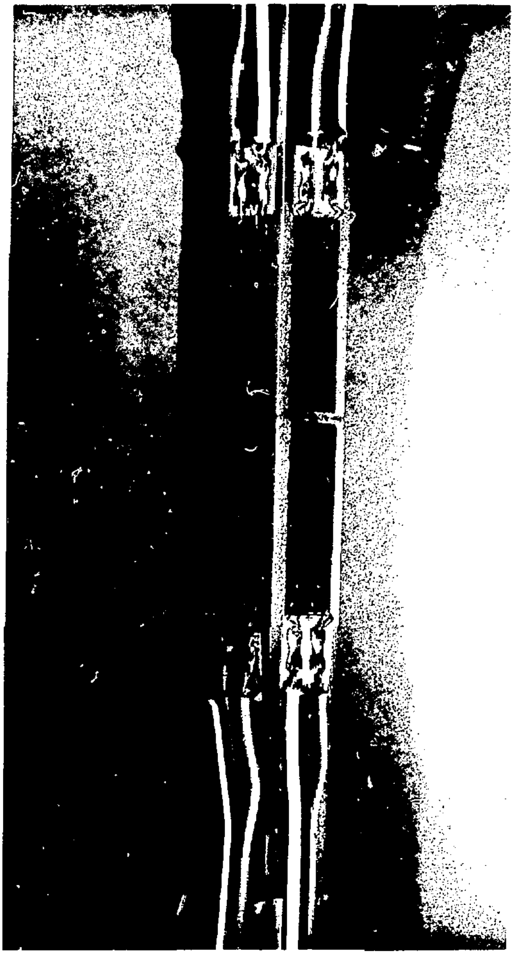

Fig. 1. Magnetoresistance test gages bonded to ETP copper test bar (WK-15-250BG-350 strain gages, Lot No. DG-K09FG14).

coating was applied over the strain gages. Continuous three-wire leads connected each strain gage to its separate equal-resistance-arm bridge located at ambient temperature. We tested these eight strain gages for magnetoresistance.

Four more strain gages identical to those above were bonded to the copper bar near one end using AE-10 adhesive. These strain gages measured the strain in the test bar and were not exposed to a significant magnetic field (less than 0.22 T when the magnet was producing 12 T). These gages monitored the strain in the test bar and its variation during testing.

The test bar was mounted in Deis' cryogenic tensile test apparatus (Fig. 2).[17] A load cell at ambient temperature monitored the force on the copper bar. We used the tensile test apparatus in the load-control mode during testing.

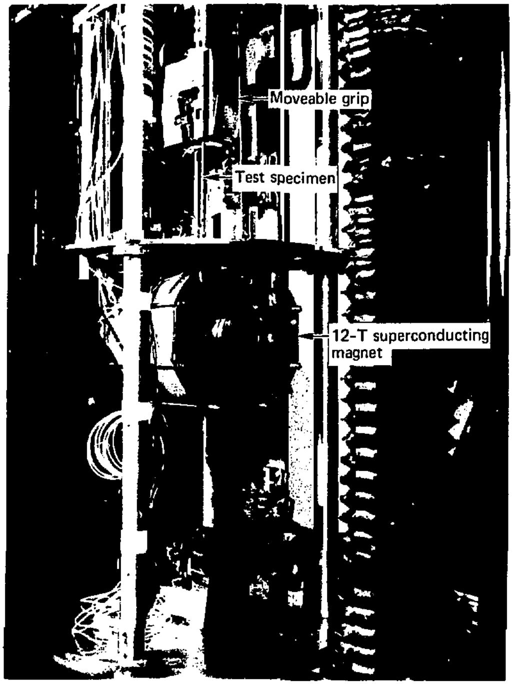

Fig. 2. Tensile-test apparatus showing superconducting magnet centered over magnetoresistance test gages on ETP copper test bar.

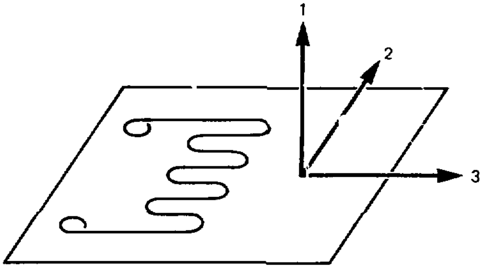

Fig. 3. Magnetic field directions relative to strain gage geometry.

A superconducting magnet with a field strength up to 12 T (Fig. 2) was centered over the eight strain gages at the middle of the copper test bar. The magnetic field was normal to the grid-plane of four of the strain gages (direction 1 in Fig. 3). For the other four strain gages, the magnetic field was oriented in the grid-plane and perpendicular to the strain-sensitive axis of the strain gages (direction 2 in Fig. 3). The magnetic field was about the same (within 1%) at all eight gage locations.

A helium cryostat enclosed the superconducting magnet and the full length of the copper test bar, including the grips at each end. For all tests, the entire copper test bar was immersed in liquid helium (4.2 K).

We measured the strain gage data with a computer-controlled data acquisition system. This system powered the channels sequentially with pulsed constant current. It measured the output voltage with an integrating digital voltmeter without amplification at the rate of 10 channels/s. We used a standard strain gage current of 5 mA. Scaled data were available during the test on a teletypewriter; unscaled data were available on a fast printer. The data were analyzed and plotted from this tape. The measurements system inaccuracy was about 2 µm/m with a resolution of 0.5 µm/m.

We temporarily connected a BLH Model 120 strain indicator to two of the strain gage channels at zero magnet current and at 12 T for all runs. We wanted to determine if spurious voltages were being introduced into the strain gage circuits. This strain indicator supplied the strain gage bridge with a 3.5-V-rms, 1-kHz sinusoidal carrier to measure strain with a resolution of ~2.5 µm/m.

Experimental Procedure for Measuring Strain Gage Magnetoresistance

The copper bar was strained sequentially to 200, 900, 2900, and 8900 µm/m. At each strain level, we maintained the strain in the copper bar nominally constant and varied magnetic field strength from the value corresponding to zero magnet current to 12 T and then back to the zero magnet current field strength. The magnetic field was held constant while magnetoresistance data was measured.

When the superconducting magnet was cooled from ambient temperature to 4.2 K, the magnetic field strength was zero for zero magnet current. After excursions to 12 T, the residual magnetic field strength at zero magnet current was not zero; it typically was 0.35, 0.43, or 0.5 T.

The AE-10 adhesive that bonded the four remote reference strain gages to the copper bar failed at about 6000 µm/m.

At 8900 µm/m strain, the copper bar continued to creep at constant load. To achieve a constant strain level, we increased the strain to about 10,000 µm/m and then reduced it elastically to a stable 8900 µm/m.

Following the 8900 µm/m test, we reduced the tension force on the bar to zero and relaxed the strain in the copper bar to a final residual tension strain of 6300 µm/m. The copper bar was carefully cut to a length of about 0.25 m with the eight test strain gages still in the middle. We centered this test bar in the horizontal bore of the magnet and carefully supported it so that no spurious loads were introduced. In this orientation, the magnetic field was parallel to the grid-plane along the strain-sensitive axis of all eight gages (direction 3 in Fig. 3). We cooled the system to 4.2 K and varied the magnetic field strength from 0 to 12 T and back to 0.35 T (zero magnet current).

Results of Magnetoresistance Tests

Table 1 details the results of all tests. We used a gage factor of 2.26 at 4.2 K. The dc field strength was zero only at the start of the 200-µm/m and 6300-µm/m runs. Field direction is listed as 1, 2, or 3 (Fig. 3).

We corrected all data for any variations in the nominal strain during the 200-, 900-, and 2900-µm/m runs by using the data from the reference strain gages at one end of the test bar. Because the reference gages failed at about 6000 µm/m, we corrected the data from the 8900-µm/m run for variations in nominal strain by using the load-cell output. This was not as accurate as using the reference gages; hence this data is of slightly lower quality compared to the other runs. The data from the 6300-µm/m run was not corrected for strain variations because the bar was not loaded during this run.

The 900-, 2900-, and 8900-µm/m runs started at zero magnet current but not zero magnetic field. For these runs, we assumed the strain error at 1-T field strength relative to 0-T field strength to be the same as the data for the 200-µm/m run. The rest of the measured data for these three runs was referenced to these assumed 1-T values.

To interpret Table 1, consider a typical data point such as 400 (2,-1) at a nominal strain level of 200 µm/m, in field direction 1, at a dc magnetic field of 12 T. The 400 µm/m is the average strain-error value for the four strain gages 5-8 inclusive. The (2,-1) are the differences between the average value and the extrema of these four gages, which in this case are 402 and 399 µm/m.

These data are plotted in Fig. 4. The open circles are the average values for all the tabulated averages in Table 1. For example, the open circle at 6 T is the simple average of the nine values for increasing field (150, 151, 148, 149, 147, 148, 144, 144, and 151 µm/m) and the nine values for decreasing field (143, 144, 144, 146, 142, 142, 138, 137, and 144 µm/m), which averages to 145 µm/m. The upper and lower brackets shown in Fig. 4 are obtained by finding the highest and lowest strain values at 6 T regardless of run. For this specific example, these values are 154 and 134 µm/m.

A polynomial equation has been least-squares-curve-fit to this data (B = magnetic field strength):

$$\text{Strain error} = a_0 + a_1 B + a_2 B^2 + a_3 B^3 + a_4 B^4,$$

where

$$a_0 = -8.9681$$
$$a_1 = -9.3437$$
$$a_2 = 9.4866$$
$$a_3 = -0.7269$$
$$a_4 = 0.0198$$

The equation fits all data within ±2 µm/m except for 0 T, where the difference is 9 µm/m.

The data from the 1-kHz sinusoidal carrier excitation strain indicator and the pulsed constant current measuring system were in all cases identical, within the 2.5 µm/m resolution of the strain indicator. There was no evidence that spurious voltages were present anywhere in the strain-gage circuits.

Discussion of Results

Referring to Fig. 4, it appears that the magnetoresistance for a total of eight strain gages at 4.2 K is independent of

- magnetic field direction,
- increasing or decreasing field (hysteresis), and
- tension strain levels ranging from 200 to 8900 µm/m.

Table 1. Results of magnetoresistance tests.

Strain level (µm/m)	200		900		2900		8900		6300
Strain-gage No.	5-8	1-4	5-8	1-4	5-8	1-4	5-8	1-4	1-8
Field direction	1	2	1	2	1	2	1	2	3
DC magnetic field (T)	Strain error[a] (µm/m)								
0	0	0	—	—	—	—	—	—	0
0.35	—	—	-6(2,-1)	-6(2,-3)	—	—	—	—	-10(2,-2)
0.43	—	—	—	—	-6(1,-1)	-6(3,-3)	—	—	-10(2,-2)
0.5	—	—	—	—	—	—	-6(2,-1)	-4(2,-4)	-10(2,-2)
1	-9(1,-1)	-8(2,-4)	-9(1,-1)[b]	-8(2,-4)[b]	-9(1,-1)[b]	-8(2,-4)[b]	-9(1,-1)[b]	-8(2,-4)[b]	-8(2,-4)
2	7(0,-1)	8(2,-4)	5(1,-1)	5(3,-4)	5(1,-1)	5(3,-4)	3(1,-1)	3(2,-4)	8(2,-3)
3	33(1,-1)	34(3,-4)	31(1,-1)	32(3,-5)	—	—	—	—	36(2,-4)
4	70(1,0)	71(3,-4)	67(1,-1)	67(4,-5)	66(1,-1)	67(3,-5)	63(1,0)	63(3,-4)	72(2,-4)
5	108(1,0)	109(3,-4)	105(1,-1)	105(4,-5)	—	—	—	—	108(4,-3)
6	150(1,-1)	151(3,-4)	148(1,-1)	149(4,-6)	147(1,0)	148(3,-5)	144(1,-1)	144(3,-5)	151(3,-4)
7	192(1,0)	193(4,-5)	191(1,-1)	192(4,-7)	—		—	—	192(3,-5)
8	235(1,-1)	236(4,-5)	234(1,-1)	234(5,-6)	—	—	—	—	235(3,-6)
9	278(1,-1)	279(3,-6)	276(1,-1)	277(4,-6)	274(1,-1)	274(3,-5)	271(1,-3)	270(4,-5)	277(3,-6)
10	319(1,-1)	320(3,-5)	319(1,-1)	319(5,-6)	—	—	—	—	318(4,-7)
11	360(1,-1)	363(2,-1)	359(1,-1)	360(5,-7)	—	—	—	—	358(5,-7)
12	400(2,-1)	402(4,-6)	401(1,-1)	402(6,-7)	398(2,-1)	398(2,-4)	393(2,-3)	393(4,-5)	397(5,-7)
11	359(1,-1)	359(4,-6)	358(1,-1)	359(5,-8)	—	—	—	—	356(7,-8)
10	316(1,-1)	318(3,-6)	316(2,-1)	318(5,-8)	—	—	—	—	314(7,-9)
9	272(1,0)	274(4,-6)	273(1,-1)	275(7,-8)	272(1,-1)	272(3,-5)	266(1,-2)	265(4,-4)	272(6,-8)
8	229(0,-1)	230(4,-6)	229(1,-1)	231(6,-8)	—	—	—	—	228(7,-9)
7	186(0,-1)	187(4,-6)	185(1,-1)	187(5,-8)	—	—	—	—	186(7,-9)
6	143(0,-1)	144(4,-6)	144(1,-1)	146(6,-8)	142(1,-1)	142(3,-4)	138(1,-2)	137(4,-3)	144(8,-10)
5	99(1,-1)	102(3,-6)	101(1,-1)	103(6,-8)	—	—	—	—	101(9,-10)
4	62(0,-1)	64(3,-5)	63(1,-1)	65(5,-8)	61(1,-1)	62(2,-4)	58(1,-2)	56(4,-2)	62(6,-9)
3	25(0,-1)	27(3,-5)	27(1,-2)	29(6,-8)	—	—	—	—	27(9,-9)
2	3(4,-3)	3(2,-5)	1(1,-2)	4(5,-8)	2(1,-1)	3(2,-4)	0(1,-1)	-1(3,-2)	0(10,-9)
1	-12(1,-1)	-9(3,-4)	-11(1,-1)	-9(6,-7)	-10(2,-1)	-10(3,-2)	-9(2,-1)	-10(3,-1)	-13(10,-7)
0.5	—	—	—	—	-7(1,-1)	-7(2,-2)		—	—
0.43	—	—	-7(1,-2)	-5(5,-7)	—	—	-5(2,-2)	-6(2,-2)	—
0.35	-8(1,-1)	-5(3,-5)	—	—	—	—	—	—	-10(11,-7)

[a] Maximum variation in parenthesis.

[b] Data from 200-µm/m run.

The maximum variation in magnetoresistance for eight strain gages, three magnetic field directions, five tension strain levels, and increasing and decreasing field strength was about ±10 µm/m at any value of magnetic field. This is well within the acceptable variation for practical strain measurements for stress analysis. The magnetoresistance is essentially linear with magnetic field from 4 to 12 T.

The data in Fig. 4 are similar to data reported by Greenough[12] to 2.5 T, Walstrom[11] to 6 T, and Hartwig[13] to 7 T for Micro-Measurements modified Karma alloy strain gages at 4.2 K.

For at least one strain gage, type WK-15-250BG-350, Walstrom[11] observed an increase in magnetoresistance of about 13 µm/m per 1000 µm/m of nominal strain on an aluminum test beam from 3 to 6 T. We did not observe any such strain dependence of magnetoresistance for strain levels from 200 to 8900 µm/m.

Greenough[12] observed an anomaly in the magnetoresistance for two SK-09-031DE-350 strain gages from the same lot number, both of which were tested in fields to 2.5 T and with fields perpendicular and parallel to the gage. The magnetoresistance for one gage followed the characteristic curve expected for Karma alloy gages. The other gage of the same lot number exhibited nearly zero magnetoresistance at fields to 2.5 T. We have not observed such an anomaly either in the eight WK-15-250BG-350 strain gages reported here or in preliminary magnetoresistance measurements performed on four WK-15-125AD-350 strain gages.

Although we have not measured the magnetoresistance of strain gages in compression, we would expect the same results as in Fig. 4. It seems logical that if the magnetoresistance is strain-level independent from +200 to +8900 µm/m, then this independence should hold true for compression strains.

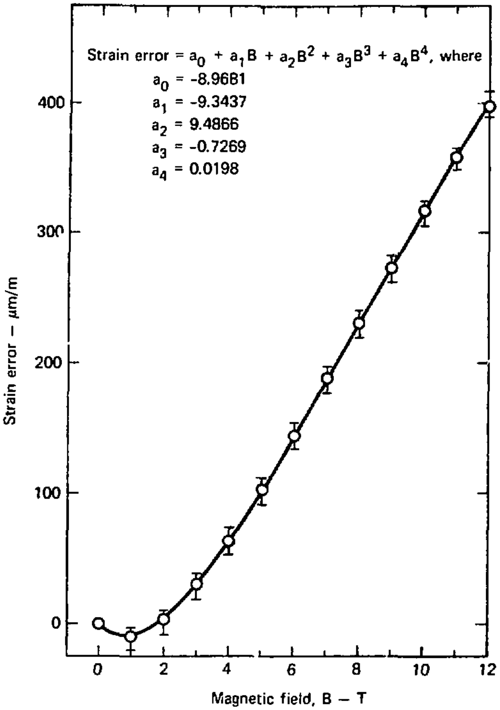

Fig. 4. Magnetoresistance strain error calibration curve as function of magnetic field at 4.2 K (WK-15-250BG-350 strain gages, Lot No. DG-K09FG14). Summary of data for eight strain gages, three field directions, strain levels of 200, 900, 2900, 8900, and 6300 µm/m, and increasing and decreasing fields.

Conclusion

We measured the magnetoresistance for eight of our standard strain gages (WK-15-250BG-350, Lot No. DG-K09FG14) for magnetic fields to 12 T at 4.2 K. The magnetoresistance data were essentially independent of field direction, increasing or decreasing field, and tension strain levels from 200 to 8900 µm/m. The data were essentially a unique function with magnetic field and were least-squares-curve-fit by a polynomial equation. The variation in magnetoresistance data was typically ±10 µm/m, which is negligibly small for practical stress analysis. This magnetoresistance calibration curve will enable us to correct measured data for magnetic field effects and make practical strain measurements on large superconducting magnets.

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