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COPPER MAGNETORESISTANCE DEVICES AS MAGNETOMETERS

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Cleveland, Ohio

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SUMMARY

An experimental investigation was initiated to select the most desirable combination of wire diameter and resistance ratio for use as a copper magnetoresistance magnetometer. Eight different polycrystalline copper wire samples were investigated; the diameters of the samples ranged from 25.4×10^{-6} to 254×10^{-6} meter, and their resistance ratios ($R_{300^\circ K}/R_{4.2^\circ K}$) ranged from 59.5 to 1005. The resistances of the samples were measured over the temperature span of 4.2° to 30° K and in magnetic fields up to 11.5 teslas. The samples were compared on the bases of the changes in ordinary resistance and magnetoresistance over the temperature range.

Polycrystalline copper displayed several desirable magnetometer properties. The magnetoresistance changed linearly with increasing magnetic field above a certain minimum field value that depended on the resistance ratio of the sample. The resistance of the lower-resistance-ratio copper samples was constant in the range from 4.2° to 15° K. The magnetoresistance of all the samples tested was independent of temperature from 4.2° to 20° K. Of the samples tested, the 25.4×10^{-6}-meter-diameter sample with a resistance ratio of 155 was selected as having the best combination of desirable characteristics for general use.

INTRODUCTION

The development of high field-strength cryogenic and superconducting magnets has generated interest in small magnetometer elements capable of operating at very low temperatures. Hall effect devices (ref. 1) and magnetoresistance sensing elements are two such magnetometer elements. Materials whose magnetoresistance characteristics do not saturate and which exhibit nearly linear changes in resistance as a function of field strength are particularly desirable. Much work has been done by numerous researchers

(e. g., refs. 2 to 4) on the resistive properties of copper. Two copper magnetoresistance magnetometers have been reported in references 5 and 6. There was, however, a need for additional information on magnetometer properties over a range of resistance ratio ($R_{300^{o} K}/R_{4.2^{o} K}$), wire diameter, temperature, and magnetic field. In particular, the applicability of copper magnetoresistance magnetometers in a varying temperature environment had not been investigated previously.

To obtain this information, an investigation encompassing a range of wire size, temperature, and magnetic field was initiated using polycrystalline copper of various resistance ratios. Eight different copper wire samples were studied; the diameters of the samples ranged from 25.4×10^{-6} to 254×10^{-6} meter, and the resistance ratios ranged from 59.5 to 1005. The resistances of the samples were measured over the temperature span of 4.2^{o} to 30^{o} K and in magnetic fields up to 11.5 teslas. The various samples were compared on the bases of the fractional change in resistance over the temperature range, the fractional variation in resistance over the magnetic field range, and the variation of magnetoresistance with temperature changes. A Kohler (ref. 2) plot of the results was also made to determine its validity over the ranges of the variables investigated. The results were then analyzed to determine which of the samples could best be utilized as a magnetometer.

APPARATUS AND TESTS

The magnetic field was provided by a 5-tesla superconducting magnet with an inside diameter of 5.08 centimeters. The uniformity of the magnetic field varied by not more than 1 percent within a 2.54-centimeter-diameter spherical volume. The magnet was calibrated by means of a rotating-coil gaussmeter, which had a maximum error of $\pm4\times10^{-3}$ tesla. The potential drop of a shunt in series with the magnet was recorded in order to monitor the field during experimental runs.

The variable-temperature sample container, shown in figure 1, was submerged in liquid helium in the bore of the magnet. By varying the current to the carbon resistors and the amount of helium gas in the container, it was possible to vary the temperature from 4.2^{o} K to beyond 50^{o} K. The temperature also could be set at any value in that range and held there for at least 2 hours. The principle of operation is straightforward; heat is introduced into the container by the joule heating of the two 100-ohm carbon resistors. The heat leak to the liquid helium bath is controlled by varying the amount of helium gas in the sample container. The temperature was measured with a calibrated 1/10-watt carbon resistance thermometer (ref. 5). Both the heaters and the resistance thermometer were cemented into the sample holder. The sample holder was fairly massive in order to ensure a uniform temperature environment for the sample.

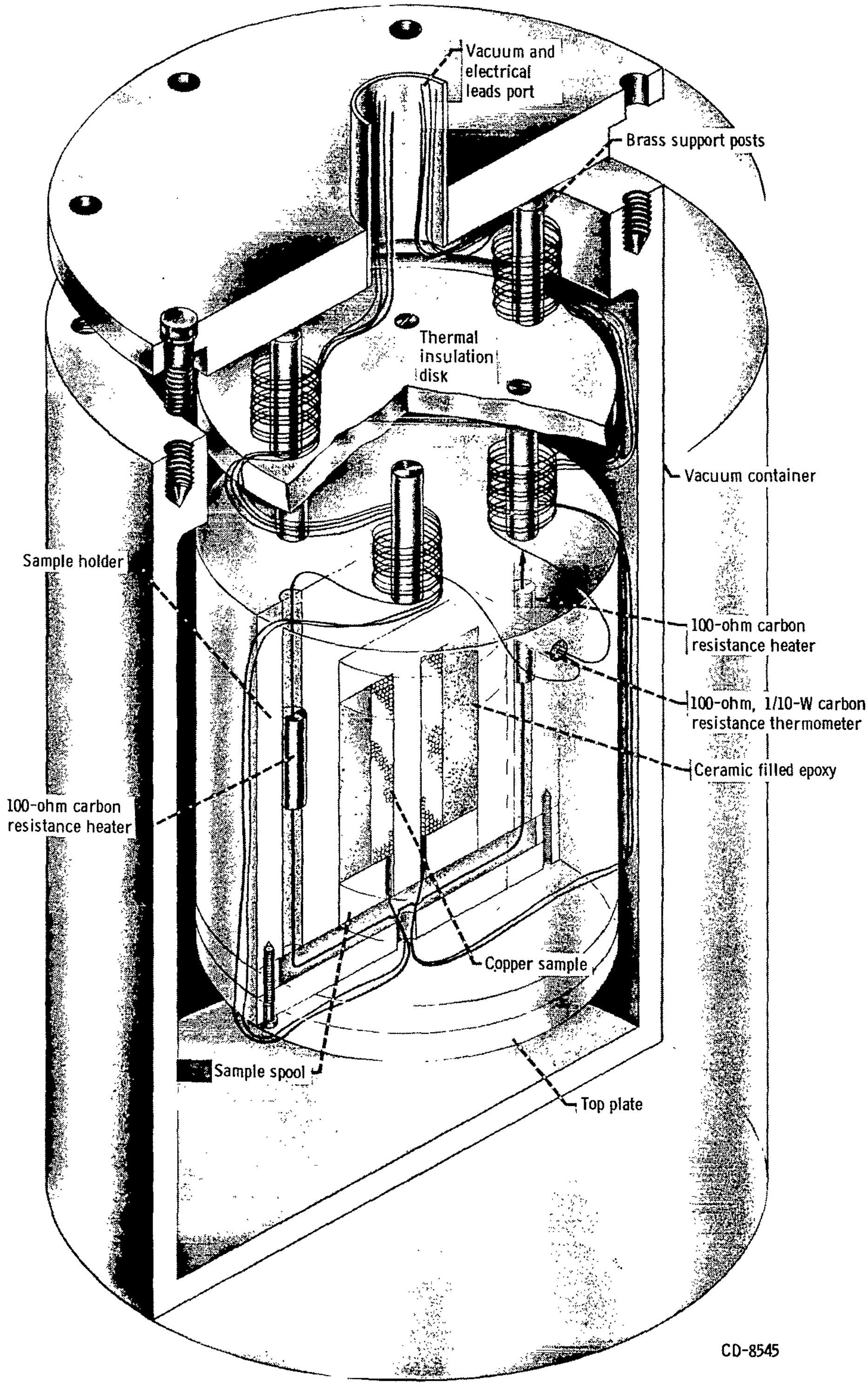

Figure 1. - Cross sectional view of variable-temperature sample container.

TABLE I. - SAMPLE PARAMETERS

Sample	Wire diameter, m	Resistance ratio	Preparation	Minimum magnetic field for which magnetoresistance is linear	Resistance at room temperature, ohm	Resistance at liquid helium temperature, ohm	Length, m	Resistivity at room temperature, ohm-m	Resistivity at liquid helium temperature, ohm-m	Sensitivity, ohm/tesla	Cross-sectional area, m^2	Volume, m^3	Sensitivity per unit volume ohm/(tesla)(m^3)
A	254×10^{-6}	361	Unannealed	0.30	0.1237	0.3425×10^{-3}	0.398	6.27×10^{-8}	1.73×10^{-10}	0.0298×10^{-2}	507×10^{-10}	2.02×10^{-9}	0.1475×10^{-6}
B	95.0	228	Drawn, unannealed	.775	3.95	17.3	1.47	7.64	3.34	.993	70.8	1.04	9.53
C	95.0	369	Drawn, annealed	.35	4.34	11.75	------	---------	-----------	1.17	70.8	---------	-------------
D	25.4	155	Unannealed	1.95	224.2	1458	5.18	8.76	5.68	54.8	5.07	2.63	209
E	25.4	68	Unannealed	2.60	220.6	3240	5.18	8.62	12.66	45.1	5.07	2.63	175
F	78.7	67.9	Commercial grade	2.75	39.15	574	10.13	7.75	11.37	8.50	48.6	49.2	1.73
G	50.8	59.5	Commercial grade	3.35	23.8	400	2.67	7.24	12.17	4.78	20.3	5.42	8.83
H	254	1005	Annealed	-----	.134	.1332	.386	6.82	6.78	.0277	507	1.96	.1417

The pertinent parameters of the samples are shown in table I. For purposes of identification each sample is assigned a letter. Samples D, E, and F were wound on copper spools as shown in figure 1. Samples B, C, and G were wound on fiber reinforced plastic spools and were only investigated at liquid helium temperature. Samples A and H were wound around the circumference of the sample holder. Sample C was annealed at 538° C for 15 hours, and sample H was annealed at 271° C for $21\frac{1}{2}$ hours. Samples B and C were obtained by drawing sample A material through diamond dies. All the samples, with the exception of A and H, were wound noninductively to eliminate induced voltages in changing magnetic fields.

Three different types of tests were made: measurements of the resistance ratio, measurements of the variation of resistance with temperature, and measurements of magnetoresistance at selected temperatures. The resistance was measured by applying a constant current to the sample and recording the voltage output. Reversing the direction of the sample current had no effect on the voltage output.

RESULTS

The variation of resistance with temperature over the range 4.2° to 36° K was nor-

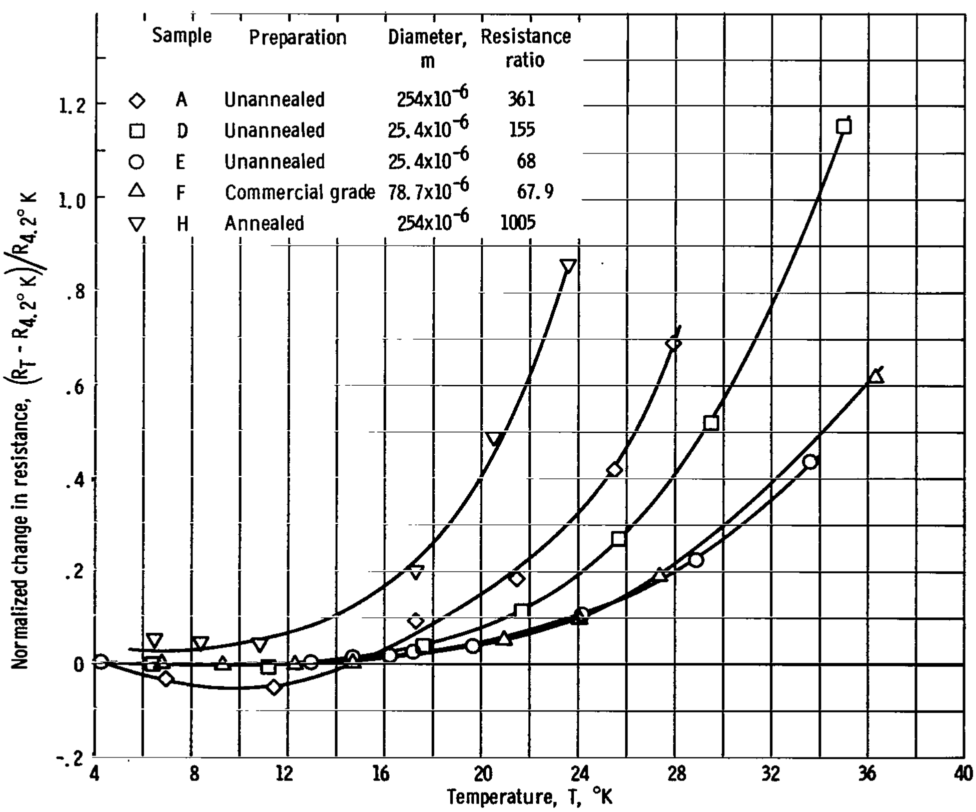

Figure 2. - Comparison of normalized resistance as function of temperature for various samples.

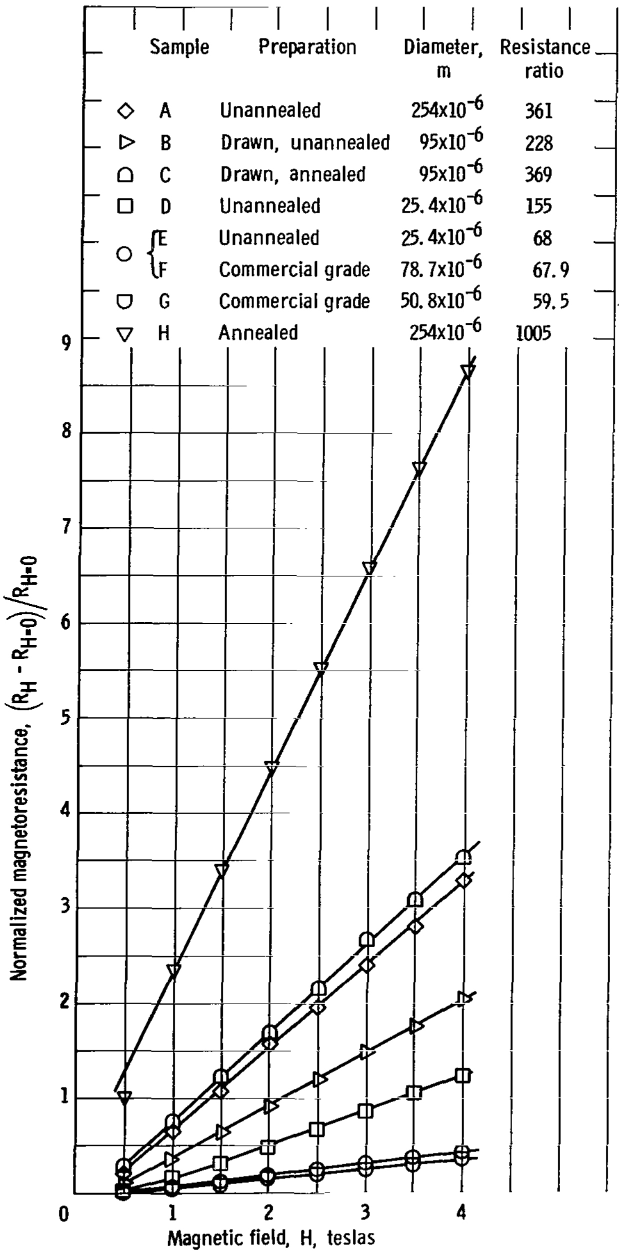

Figure 3. - Comparison of normalized magnetoresistance for several copper samples.

malized by dividing the resistance changes by the sample resistance at liquid helium temperature. The results are compared in figure 2. Two trends are immediately apparent. First, the temperature at which the curves deviate from the resistance at liquid helium temperature decreases with increasing resistance ratio. Second, the rate at which the curves increase with temperature decreases with increasing resistance ratio.

The magnetoresistance of the samples (also normalized to the resistance at liquid helium temperature) is presented in figure 3. As expected (ref. 8), the normalized magnetoresistance was strongly and directly dependent on the resistance ratio. For example, sample H had a normalized magnetoresistance 27 times greater than that of sample G. Above a certain magnetic field, which varied with the sample, all the magnetoresistance curves became linear. The value of this field (H_{min}) decreased as the resistance ratio of the sample increased. The values of H_{min} are presented in table I.

The linearity of the magnetoresistance of samples B, C, D, and E (fig. 4) was studied by means of a liquid-neon-cooled aluminum cryogenic magnet (ref. 9). Samples B, C, and D had a linear magnetoresistance over the entire range tested (2.3 to 11.5 teslas). Sample E was linear between 6.0 and 11.5 teslas. Samples F and G were not tested at high fields because they had performed almost exactly like sample E at lower fields. Samples A and H were not tested at high fields because

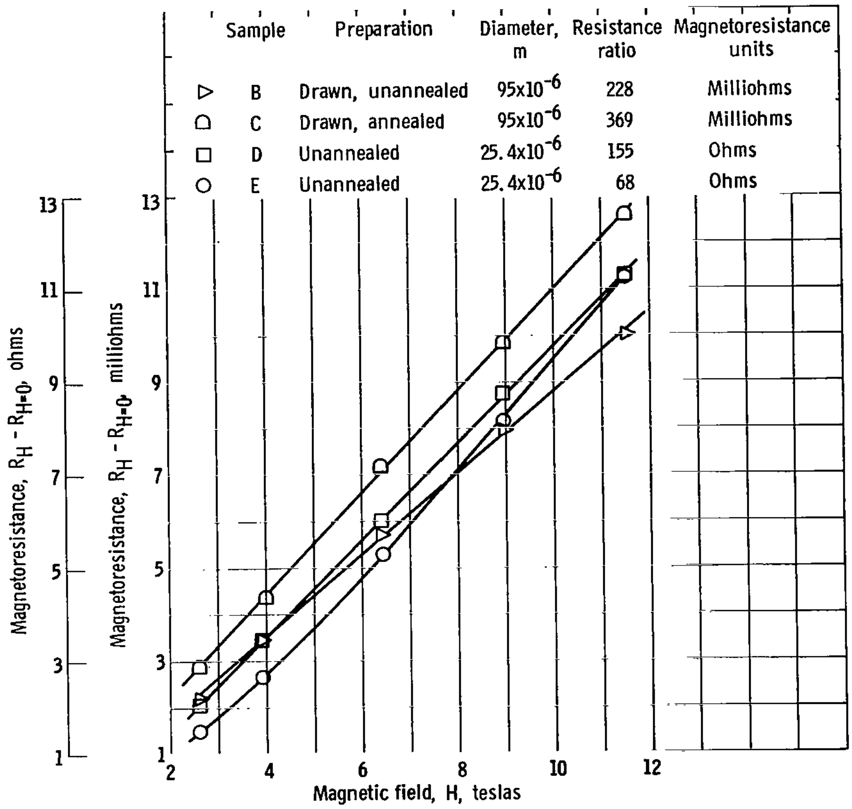

Figure 4. - High-field magnetoresistance of copper.

of their low resistance and high inductance.

For all the samples except B and C the dependence of magnetoresistance on temperature was investigated. Samples B and C were prepared for a previous experiment and were physically incompatible with the variable-temperature probe. In all cases, the magnetoresistance was independent of temperature from 4.2° to 20° K, within the experimental error of 2 percent.

The results are also presented in figure 5 as a Kohler plot in which the normalized magnetoresistance is plotted against the magnetic field times the resistance ratio between 300° K and a sample temperature of 4.2° K. Samples A, D, E, F, and G fell within a 5-percent band on the Kohler plot. Samples B, C, and H were above this band by more than 10 percent. Samples B and C diverged from the band at higher field values, and sample H appeared to be converging to the band. In all cases, the samples which were annealed, drawn, or both, subsequently were higher on the Kohler plot.

The Kohler plot usually reduces magnetoresistance curves at different temperatures onto a common curve, but in these tests it spread them apart. Sample D was chosen to demonstrate this result. In figure 6, magnetoresistance is compared at 4.3° and

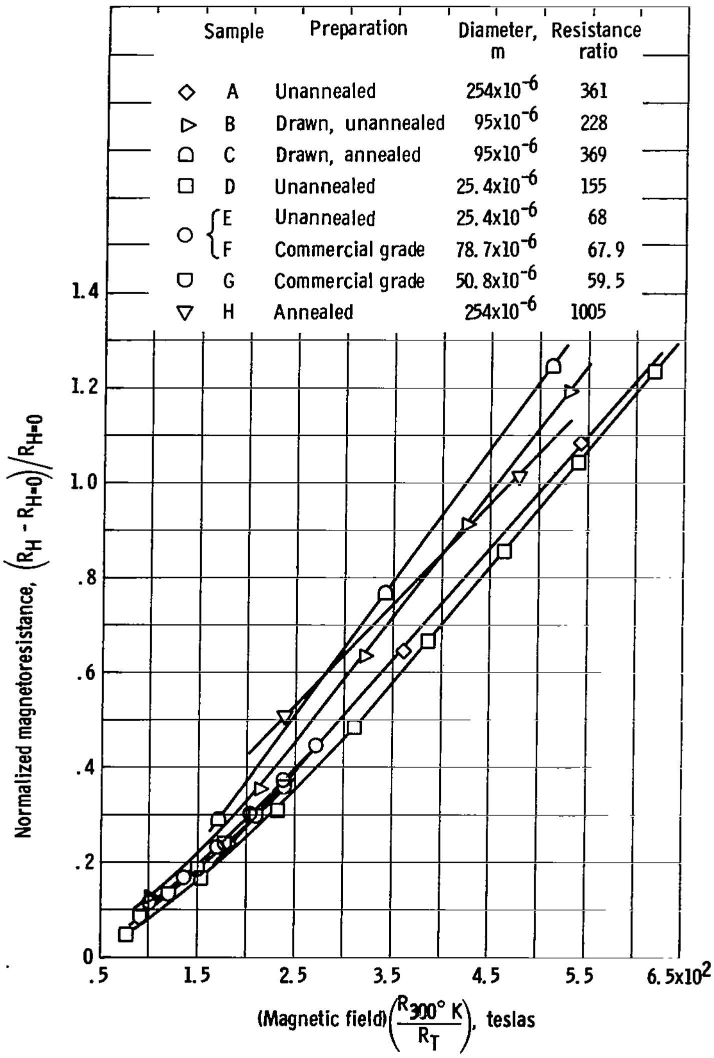

Figure 5. - Kohler plot of magnetoresistance of copper.

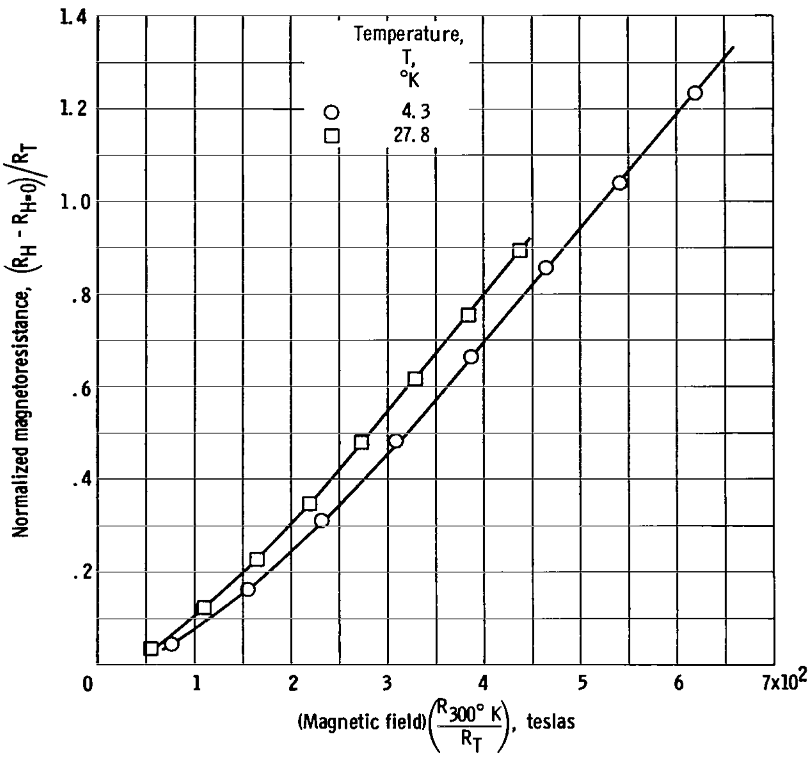

Figure 6. - Kohler plot of sample D at two temperatures. Diameter of sample, 25.4×10^{-6} meter; resistance ratio, 155.

27.8° K; the Kohler plots of the two curves differ by more than 10 percent. The curve for the higher temperature is above the lower temperature curve on the Kohler plot partly because, as stated before, the magnetoresistance was independent of temperature while the zero field resistance changed with temperature.

The magnetoresistance of wire samples of comparable resistance ratio was almost independent of wire diameter. This result may be verified in figure 3 by comparing sample A with sample C, or by comparing samples E, F, and G with each other. All the resistance and magnetoresistance characteristics were unaffected by temperature cycling between 300° and 4.2° K.

DISCUSSION

Copper has several characteristics which make it useful as a magnetoresistance magnetometer. One of these is the linearity of magnetoresistance above H_{min}. The constancy of magnetoresistance with temperature is another very desirable trait, as is the insensitivity to temperature cycling between 300° and 4.2° K. Most of the samples tested have the aforementioned characteristics. An important characteristic, which varied widely among the samples, is the sensitivity (change in resistance with magnetic field, ohm/tesla). These sensitivities are given in table I (p. 4) for the linear region of magnetoresistance. The sensitivities are also compared on a per-unit-wire-volume basis, since for many experiments low volume is desirable (e. g., the accurate measurement of small, nonuniform fields).

Other qualities of importance for some experiments are the minimum magnetic field H_{min} for which the magnetoresistance is linear, the magnetometer resistance at zero magnetic field, and the magnetometer inductance (if changing magnetic fields are to be monitored).

High normalized magnetoresistance is also desirable for ease of measurement, because the voltage changes resulting from magnetoresistance are superimposed on the normal voltage.

Under particular experimental conditions, any one of the aforementioned characteristics may dictate which sample would make the best magnetometer. In general, however, the 25.4×10^{-6}-meter-diameter sample with a resistance ratio of 155 seems to have the best combination of desirable characteristics. It has the largest sensitivity per unit wire volume (more than 10^3 times that of sample H). Its resistance is constant within 1 percent from 4.3° to 14° K. Its normalized magnetoresistance characteristic is sufficient for accurate measurement in that the magnetoresistance is large compared to the resistance. Its small diameter permits winding it into small noninductive coils. Its weakest characteristic is the relatively high H_{min} of 1.95 teslas. If enough volume is available, this problem can be remedied by surrounding the coil with iron. A high-permeability material will saturate very quickly, thereby boosting the magnetometer output into the linear region.

CONCLUSIONS

Polycrystalline copper has several desirable magnetometer properties, including specifically the behavior of resistance and magnetoresistance in a variable temperature environment. The magnetoresistance increases linearly with increasing magnetic field above a certain minimum field value that depends on the resistance ratio of the sample. The resistance of the lower-resistance-ratio copper samples is constant in the range from 4.2° to 15° K. The magnetoresistance of all the samples tested is independent of temperature from 4.2° to 20° K. On the basis of these characteristics for the samples tested, and considering the sensitivities per unit volume, the 25.4×10^{-6}-meter-diameter sample with a resistance ratio of 155 was selected as having the best combination of desirable characteristics.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, April 25, 1966,
129-02-05-09-22.

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