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TRANSVERSE MAGNETORESISTANCE OF ALUMINUM

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ABSTRACT

Because aluminum shows promise as a conductor suitable for a cryogenic magnet, its transverse magnetoresistance was studied. The measurements were made on six samples of 99.999 percent pure aluminum at 4.2°K in magnetic fields H up to 120,000 gauss, the samples having been annealed, and in two cases cold worked, so as to be in various states of strain. Valid data were obtained from four of the samples, for which the ratios (at $H = 0$) of room temperature resistivity $R_{300°K}$ to the resistivity R at 4.2°K were 1530, 1180, 1075, and 333. Since $R_{300°K}$ is essentially the same for all the samples, these ratios are proportional to the R values, which for two of the samples can be seen to be in the ratio 1530/333 or approximately 4.6. At $H = 80{,}000$ gauss, this ratio was still 4.4, showing that almost all of the resistivity decrease gained at $H = 0$ by using a less strained metal is preserved at high magnetic fields for a metal whose magnetoresistance exhibits a predominately saturating behavior. The data from the four samples were normalized fairly well by Kohler's rule, which is $\Delta R/R = f(HR_{300°K}/R)$, where ΔR is the increment to R due to the magnetic field. This indicates that further reductions in the power necessary to operate cryogenic magnets can be profitably achieved by using purer and purer aluminum.

PROBLEM STATUS

This is an interim report on one phase of the problem; work on the problem is continuing.

AUTHORIZATION

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TRANSVERSE MAGNETORESISTANCE OF ALUMINUM

INTRODUCTION

Cryogenic magnets (1) utilize the low electrical resistivities at low temperatures in pure metal conductors to attain high magnetic fields with reduced power. However, the magnetic field generated by a cryogenic magnet increases the resistivity of the conductor due to magnetoresistance and partially nullifies the resistivity decrease gained by reducing the temperature. Thus the conductor chosen for cryogenic magnets should have the smallest possible net resistivity not only at low temperatures but also in high magnetic fields. Data on the magnetoresistance of metals at low temperatures and in high magnetic fields are therefore needed in order to choose a conductor suitable for a cryogenic magnet.

Recent successes in correlating theoretical and experimental studies on the electronic energy band structure of metals and their associated Fermi surfaces (2) have clarified the essential nature of magnetoresistance. The study of magnetoresistance has in turn developed into a powerful tool for determining the topology of the Fermi surface. The transverse magnetoresistance of a metal in the limit of high magnetic fields can exhibit only two types of behavior: (a) when the applied magnetic field H is normal to a closed cross section of the Fermi surface, corresponding to closed electronic orbits, the magnetoresistance saturates, and (b) when H is normal to an open cross section of the Fermi surface, corresponding to open electronic orbits, the magnetoresistance increases quadratically with H. At high H, the magnetoresistance from the quadratic effect is generally orders of magnitude larger than that from the saturation effect. A metal can have either a single Fermi surface or multiple Fermi surfaces, and both types are generally very complex and anisotropic. The Fermi surface can contain both open and closed cross sections and consequently have both open and closed electronic orbits. Even for the single Fermi surface of any of the noble metals, with only one valence electron, both open and closed orbits exist. For example, the transverse magnetoresistance of a copper single crystal exhibits respectively either a fully saturating or a quadratic behavior depending upon whether the orientation of H with respect to the crystalline axis is normal to a closed or an open cross section of the Fermi surface (3). The alkali metal sodium is the closest known approximation to an isotropic free electron metal, and its single Fermi surface should have only closed cross sections. Therefore, the transverse magnetoresistance of sodium should exhibit saturation at any orientation, but this has not as yet been clearly observed (4). Aluminum with three valence electrons has three highly anisotropic Fermi surfaces according to the free electron model of Harrison (5). All three surfaces have only closed cross sections normal to H even though one of the surfaces is multiply connected and is highly open in appearance in three-dimensional space. Therefore, the transverse magnetoresistance of an aluminum single crystal should saturate at any orientation. For polycrystalline metals with intrinsic open and closed orbits, the net result is generally a linear dependence as in copper (6). For virtually all other metals except indium, the magnetoresistances are so high that they are not practical for cryogenic magnets.

The variation of the magnetoresistance with temperature, purity, or state of strain for a given metal can generally be normalized by the relation

$$\frac{\Delta R}{R} = f\left(H \frac{R_{300\,^\circ K}}{R}\right)$$

known as Kohler's rule (7), where R is the resistivity at zero magnetic field at a given low temperature T, ΔR is the resistivity increment at T due to H, and $R_{300°K}$ is the room temperature resistivity. For a single crystal, the functional dependence of $\Delta R/R$ is different for different orientations of H with respect to the crystalline axis. For polycrystalline metals, crystal orientation no longer has meaning and Kohler's rule yields a single function which is independent of the specimen orientation with respect to H.

For polycrystalline metals exhibiting a linear or quadratic magnetoresistance, the more pure and less strained specimens of a given metal at a given low temperature will have lower resistivities at $H = 0$ but will have higher magnetoresistances. According to Kohler's rule, $\Delta R/R$ will increase continuously with H to relatively high values at high H so that the resistivities of both the better and the poorer specimens will tend toward the same resistivity in the limit of high H. Thus, metals having a linear or quadratic magnetoresistance are not very useful for cryogenic magnets since the resistivity decreases gained at $H = 0$ by lowering the temperature or by using purer or less strained specimens are largely nullified by the magnetoresistance at high H.

Some polycrystalline metals exhibit a saturating magnetoresistance, and $\Delta R/R$ approaches a constant value independent of T in the limit of high H. This saturation value of $\Delta R/R$ has been found to be generally much smaller than the high H value of $\Delta R/R$ for metals having a linear or quadratic magnetoresistance. If Kohler's rule applies to a metal with a saturating magnetoresistance, it requires that the saturation value of $\Delta R/R$ be independent of the temperature or the purity and state of strain. For such a metal, therefore, the resistivity decreases gained at $H = 0$ by lowering the temperature or by using purer and less strained metals would be essentially preserved at high H instead of being largely nullified as in the case of the nonsaturating metals. For basic research and for the practical choice of a conductor for cryogenic magnets, it is important to know whether Kohler's rule is applicable to a saturating metal. However, Kohler's rule has not been adequately tested for a saturating metal in steady high magnetic fields.

The purpose of this paper is to test the validity of Kohler's rule for a metal with a saturating magnetoresistance in the high steady magnetic fields up to 120,000 gauss available at the Naval Research Laboratory. Aluminum was chosen as the metal to study, since it has exhibited a saturating magnetoresistive behavior in previous experiments at lower steady magnetic fields (8,9) and in pulsed high magnetic fields (10).

EXPERIMENTAL DETAILS

The six aluminum samples measured in these magnetoresistance experiments were all obtained from a single 0.018-in. diameter wire of "Super Raffinal" aluminum (99.999 percent pure) produced by Aluminium-Industrie-Aktien-Gesellschaft, Switzerland. The current and potential probes were ultrasonically soldered to the aluminum samples. Except for sample Al V, the experiments were performed in the 1-1/8-inch-diameter cylindrical bore of an air-core Bitter (11) solenoid capable of producing high steady magnetic fields up to 120,000 gauss. The actual cylindrical working space at liquid helium temperatures was 9/16 inch in diameter. In order to perform truly transverse magnetoresistance measurements in this 9/16-inch-diameter working space, the distance between the potential probes was limited to between 1/4 and 3/8 inch. Sample Al V was a tightly wound noninductive helix, so that the magnetoresistance measurements were essentially transverse. The distance between the potential probes on Al V was 78 mm, and the magnetoresistance measurements were performed in the 4-inch-diameter cylindrical bore of a Bitter solenoid capable of producing steady magnetic fields up to 85,000 gauss. Samples Al I, Al II, Al III, and Al VI were annealed at 400°C for 16 hours. Samples Al IV and Al V were annealed at 330°C for 2 hours. In addition, Al V was moderately cold worked and Al VI was slightly cold worked. The resistance ratios at $H = 0$ upon decreasing the temperature from 300°K to 4.2°K ($R_{300}/R_{4.2}$) ranged from 333 for Al V to 1630 for Al III.

The magnetoresistance curves for all the samples were recorded continuously on an x-y recorder as the magnetic field was varied smoothly and slowly. The magnetic field, which is directly proportional to the magnet current, was recorded on the x axis by measuring the voltage across a known resistance in series with the magnet. The resistance of the aluminum samples was measured by a four-terminal potentiometric method. The voltage between the potential probes on the samples was recorded on the y axis after being appropriately amplified by a dc amplifier (Keithley Model No. 149 millimicrovoltmeter) with a noise level of $\sim 10^{-9}$ volt. Errors due to small Hall effect voltages superimposed on the magnetoresistance curves were eliminated by reversing the direction of the applied magnetic field.

RESULTS AND DISCUSSION

The tests on the validity of Kohler's rule for a metal with a saturating magnetoresistance were performed at 4.2°K by varying the state of strain of the aluminum samples. The results on the magnetoresistance of Al I and Al II were anomalously different. Although both Al I and Al II had a value of $R_{300}/R_{4.2}$ = 1460, the values of $\Delta R/R$ at H = 120,000 gauss was 2.5 for Al I and 10 for Al II. Upon a close examination of these samples, a solder bridge was noted between the current and potential contacts at each end of the samples which was more pronounced for Al II than for Al I. These solder bridges cause a nonuniform current distribution at the potential contacts which in turn causes a geometrical magnetoresistive effect (12) to be superimposed upon the normal magnetoresistance. Since these samples have a very low resistance in the ~3/8-inch length between the potential contacts, and since aluminum has a small normal magnetoresistance, this superimposed geometrical magnetoresistance can become quite large compared to the normal magnetoresistance and most likely explains the anomalous results for Al I and Al II. In view of this difficulty, the results for both Al I and Al II were not considered further. For the remaining aluminum samples, the ultrasonically soldered current and potential probes at each end of the samples were separated by a distance equal to at least two diameters of the sample, so that a uniform current distribution was established at the potential probes.

The increase of resistivity due to the applied magnetic field is shown in Fig. 1 for Al III and Al V. For the six specimens measured, $R_{300}/R_{4.2}$ was highest for Al III at 1530 and lowest for Al V at 333. The magnetoresistance of Al III appears at first sight to be saturating at about 15,000 gauss, but actually exhibits a small linear increase. At $H = 0$, the resistivity of Al V is ~4.6 times greater than the resistivity of Al III. At H = 80,000 gauss, the resistivity of Al V is still ~4.4 times greater than the resistivity of Al III. Thus, almost all of the resistivity decrease gained at $H = 0$ by using a less strained metal (Al III as compared to Al V) is preserved at high magnetic fields for a metal whose magnetoresistance exhibits a predominantly saturating behavior.

Figure 2 shows a Kohler plot at 4.2°K of $\Delta R/R$ versus $HR_{300}/R_{4.2}$ for the transverse magnetoresistance of Al III, Al IV, Al V, and Al VI. The widely different magnetoresistance curves for Al III and Al V as shown in Fig. 1 are normalized fairly well by the Kohler plot. The values for $\Delta R/R$ lie between 2 and 2.2 for $HR_{300}/R_{4.2} = 10^8$ in Fig. 2. Thus, Kohler's rule is applicable to the transverse magnetoresistance of polycrystalline aluminum which exhibits a predominantly saturating behavior. These results agree substantially with the previous lower field results of Yntema (8) and Borovik (9) and the high pulsed field results of Luthi (10).

These results show that aluminum would be an excellent choice as the conductor for cryogenic magnets, because aluminum (a) exhibits extremely low resistivities at low temperatures in $H = 0$, and (b) exhibits only a small magnetoresistance which essentially saturates. For these reasons, the resistivity of aluminum is very low both at low temperatures and in high magnetic fields. Since the essentially saturating magnetoresistance

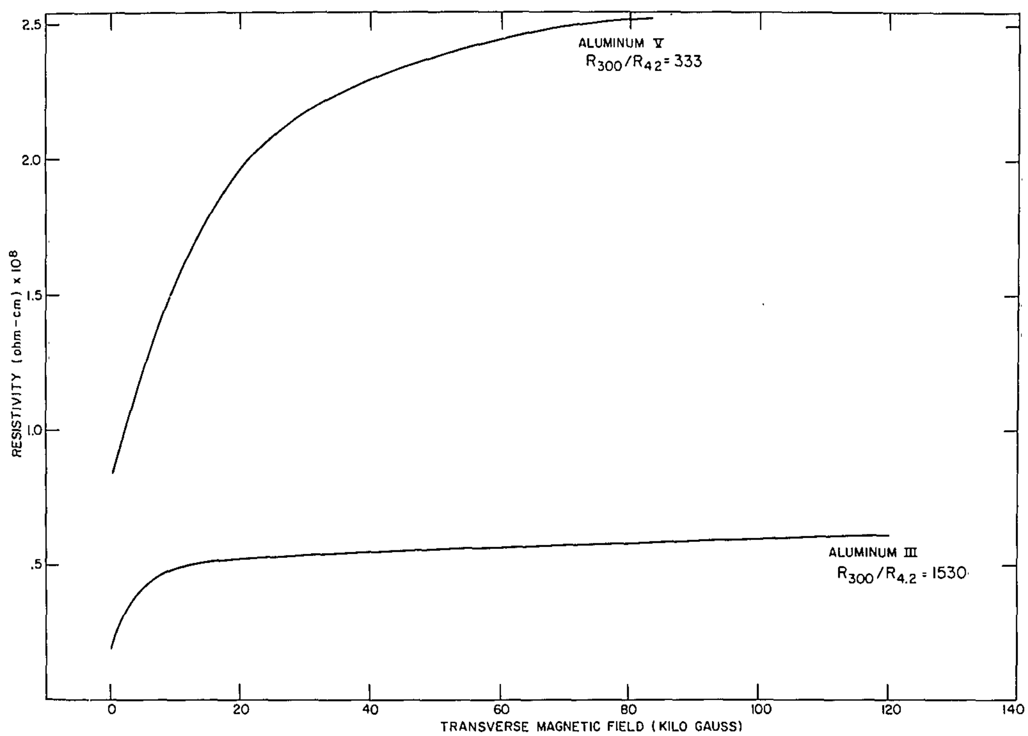

Fig. 1 - Resistivity vs magnetic field at 4.2°K for Al III (annealed) and Al V (cold worked)

of aluminum obeys Kohler's rule, further reductions in the power necessary to operate cryogenic magnets can be profitably achieved by using purer and purer aluminum. Values for $R_{300}/R_{4.2}$ up to 7000 have been reported (13) for zone-refined aluminum. Linear extrapolation of the data in Fig. 2 to the 10^9 region for $HR_{300}/R_{4.2}$ (using $H = 120{,}000$ gauss and $R_{300}/R_{4.2} = 7000$) would result in a value of ~3 for $\Delta R/R$. Thus the use of purer aluminum with manyfold lower resistivity causes only a comparatively small percentage increase in the magnetoresistance, due to its predominantly saturating behavior.

The small linear increase at high H in the transverse magnetoresistance of aluminum is of great interest for basic research on the Fermi surface, but is not of much consequence for the practical purposes of designing cryogenic magnets for which the magnetoresistance can be considered as having predominantly saturated. The magnetoresistance curves for polycrystalline aluminum in Figs. 1 and 2 can be interpreted in accordance with the description in the Introduction as follows: (a) the initial rapid approach to a seeming saturation at lower magnetic fields indicates that the magnetic field has caused almost all of the electrons to be placed into closed orbits; (b) the small linear increase at high H indicates that at least some of the remaining few electrons are in open orbits in H. These remaining few electrons in open orbits would cause a quadratic magnetoresistance by themselves. Thus the small linear magnetoresistance at high H might be due to a combination of the fully saturating magnetoresistance for almost all of the electrons and of the quadratic magnetoresistance for the remaining few electrons. If the small linear magnetoresistance is valid and not due to some subtle experimental error, and also if the above interpretation is correct, then one or more of the three Fermi

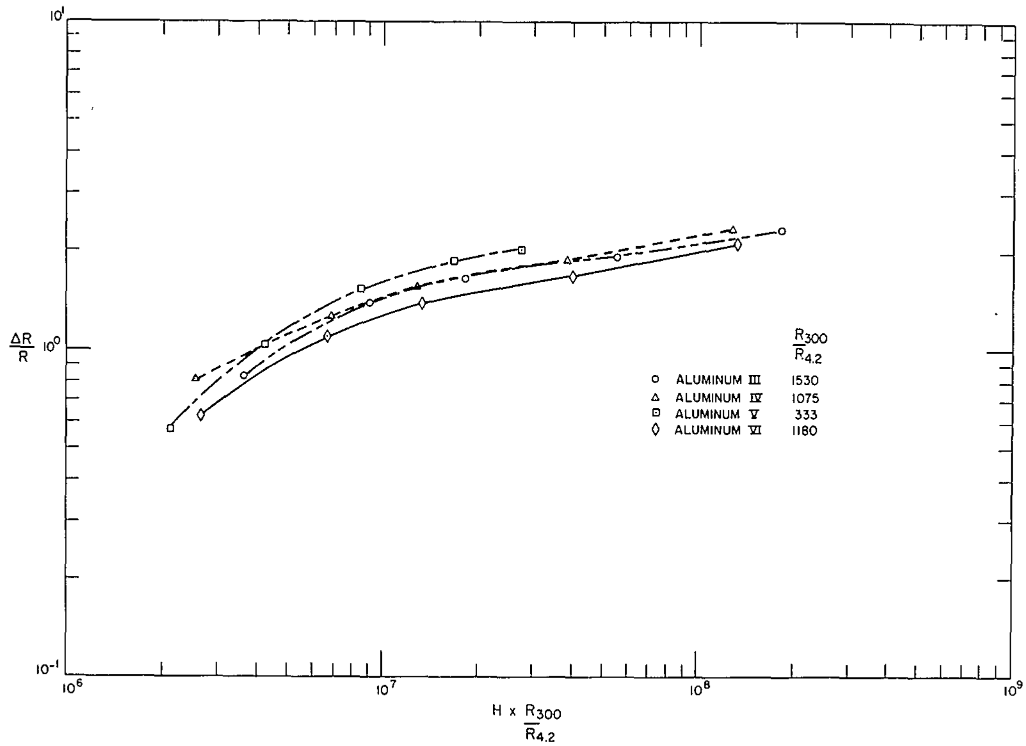

Fig. 2 - Kohler plot of the transverse magnetoresistance at 4.2°K for polycrystalline aluminum as a function of strain

surfaces proposed (5) for aluminum would have to contain open cross sections at some few orientations. Further experiments on the orientation dependence of the transverse magnetoresistance of aluminum single crystals at high magnetic fields are necessary in order to test the validity of the above interpretation.

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3. Magnetoresistance - Meas.

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