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Effect of Defect Structure on the Transverse Magnetoresistivity of Iron, Copper, and Nickel

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The effect of plastic deformation in normal metals is to increase the electrical resistivity by introducing scattering centers such as dislocations, point defects, and stacking faults. The change in resistivity with an applied magnetic field is influenced in a metal only by defects which scatter conduction electrons anisotropically. The iron, copper, and nickel specimens were plastically deformed by shock loading and tensile elongation. The transverse magnetoresistance of the annealed and deformed specimens was measured at 20°K. The results, plotted on a Kohler diagram, show that the deformed material yields a curve which is in general shifted from the annealed metal. Both positive and negative shifts have been found in the present experiments.

Electrical resistivity and magnetoresistivity were measured as a function of deformation for each metal system. The van der Pauw[1] method was used, wherein the resistivity and Hall coefficient can be measured on a specimen of arbitrary shape. The specimens used in this experiment had 0.5- by 5-mm rectangular cross sections and were 3-cm long. Three pairs of mutually perpendicular leads are attached to the specimen to measure the sample's magnetoresistance and the transverse fields. Because

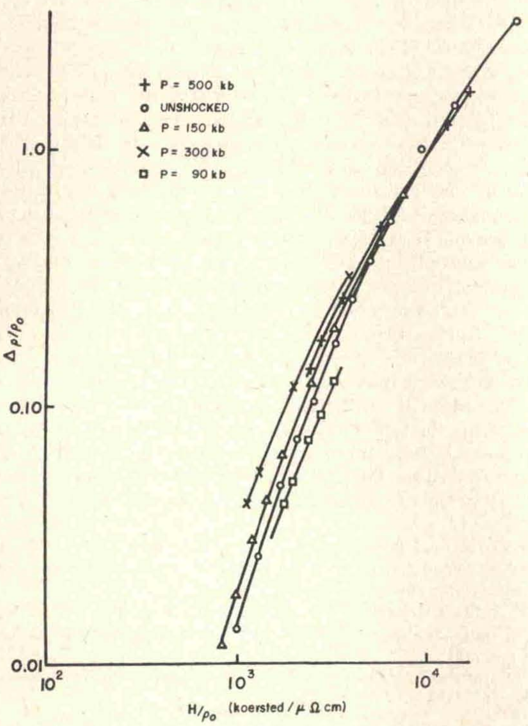

FIG. 1. Effect of plastic deformation on the transverse magnetoresistance of iron at 20°K.

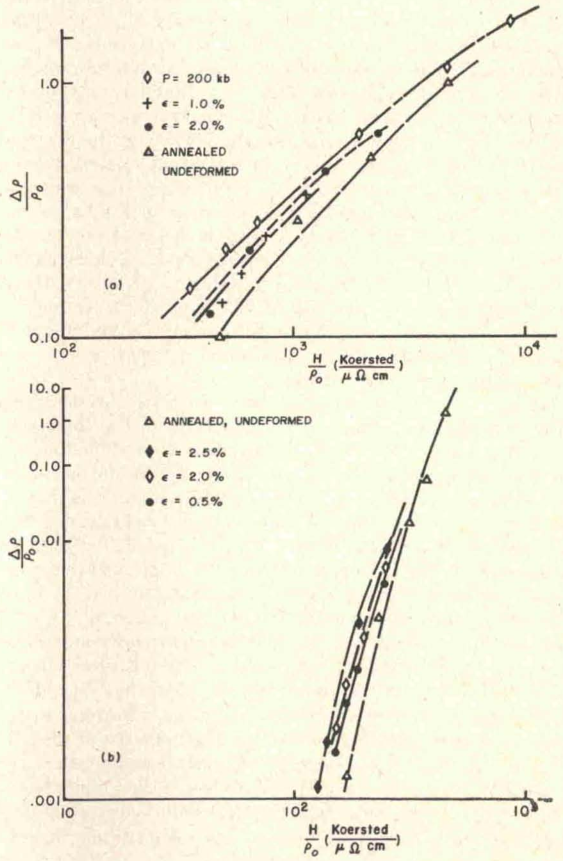

FIG. 2. Effect of plastic deformation on the transverse magnetoresistivity of (a) copper and (b) nickel.

the galvanomagnetic properties are very sensitive to the magnetic field direction, provision must be made for aligning and rigidly clamping the specimen while it is immersed in liquid helium in the magnetic field. Data was taken by recording the potential across one of the pairs of leads as a function of field intensity while holding the field direction fixed. A K-3 universal potentiometer with a Regatran power supply as a constant current source was used for electrical resistivity measurements. An electromagnet with 15-cm pole pieces and 3-cm pole gap was used for generating the magnetic field. The field was determined with a calibrated magnetic fluxmeter using a bismuth probe. The copper, nickel, and iron specimens had an impurity level of about 0.005% which was sufficient to explain the residual resistivity in terms of impurity scattering.

Prior to plastic deformation the specimens were annealed for $\frac{1}{2}$ h at 600°C to produce the desired grain diameter. It was required that a single irregularly oriented crystal be an order-of-magnitude larger than the free path of the conductions electrons, which in this case was about 1 μ. The texture was shown to be very small by x-ray diffraction studies. The flying plate technique[2] was used in shock loading, allowing for both the magnitude and geometry of the pressure pulse to be controlled by the driver plate thickness. Specimens for galvanomagnetic measurements were spark cut from a shocked foil 3 by 3 cm. Tensile specimens were elongated in an Instron machine with a metalfilm strain gauge mounted on each specimen in order to improve sensitivity.

In the first series of experiments on iron, Fig. 1, it was found that at low field strengths the shock deformation caused an upward shift of the Kohler curve. This shift increases with deformation, but is much smaller in the high-field region where $\lambda/\alpha \gg 1$ (λ is the mean-free path of a conduction electron, α is the cyclotron orbit radius). In this region the conduction electron can cover a large distance on the Fermi surface between two collisions. In the low-field region deviations from the perfect Kohler curve can be explained by an anisotropic relaxation time $\tau(\mathbf{K})$. In the isotropic case $\tau(\mathbf{K})$ is a function only of K, the magnitude of the wave vector. Any changes in τ are a result of processes which allow the interchange of energy between lattice waves. In the present work, it is believed that scattering processes due to irregularities of the lattice result in an anisotropic relaxation time, and consequently a deviation from Kohler's rule.

Figure 2 shows the effect of plastic deformation on the resistivity of copper and nickel. For the copper specimen an elongation of 2% produced a large positive shift in resistivity. However recovery treatments near 20°, 100°, and 200°C caused minor changes. These isochronal anneals are identified as Stages I–III. Annealing at 400°C (Stage V) caused a negative shift toward the original Kohler curve (Fig. 3).

It is well known that the recovery of electrical resistance after plastic deformation occurs in various stages.[3] The interpretation of these stages still presents difficulties. Investigators in the field agree, however, that Stages II–IV are due to the migration and disappearance of point defects while Stage V is due to the movement of dislocations. Stage IV in shock-loaded iron is situated at about 240°C and Stage V at 320°–740°C. After annealing at 400°C iron also showed a large negative recovery shift toward the Kohler curve as is shown in Fig. 3. At 600°C the curve returned to its original position. Therefore, for copper and iron it is believed that the shift is produced when dislocations are introduced by plastic deformation. The shift does not change when point defects are recovered. An effect has been obtained only when dislocations are available to act as anisotropic scattering centers. Severe deformation, with a high density of dislocations does not result in a less ansiotropic relaxation time, even though orientation in the annealed metal has been eliminated. This may be due to the fact that the effect observed is obtained only from dislocation distributions which are anisotropic in a region

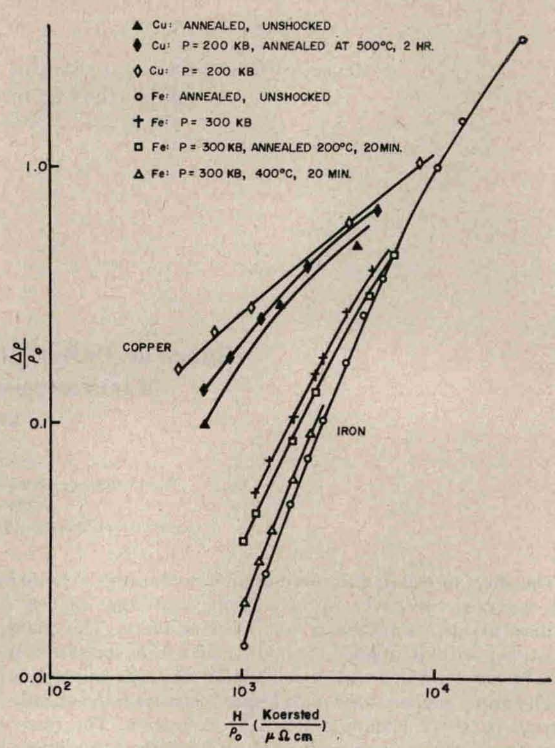

FIG. 3. Magnetoresistance of plastically deformed and recovered copper and iron.

at least as small as an electron orbit in the magnetic field. The results of our experiments agree qualitatively with the work of Jongenbuerger[4] on plastically deformed metal wires. The presence of dislocations were detected by studying the transverse magnetoresistance of single-crystal copper wires at low temperatures.

In order to rationalize the above effects, it would be necessary to know the exact nature of the defect structure and the associated stress pattern introduced by the plastic deformation. Although we cannot hope to know the details of the defect structure, there are some general statements which can be made about it. In all fcc metals broad three-dimensional tangles are made up predominately of dislocations having Burgers vectors of the active slip system. It is clear, therefore, that the defect structure is not an isotropic one, but rather highly anisotropic. Furthermore, the associated stress pattern will also be highly anisotropic. It is this substructure which is responsible for the shift from the normal Kohler curve.

The defect structure of plastically deformed iron has been studied by Carrington *et al.*[5] In the annealed condition the grains are threaded by a three-dimensional network of dislocations joining up the subboundaries. Cold working creates more dislocations which are unevenly distributed and eventually a cellular structure results. The effect structure is thus highly anisotropic giving rise to the observed magnetoresistivity effect.

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