Reprinted from
PHILOSOPHICAL MAGAZINE, Vol. 22, No. 175, p. 93, July 1970

Galvanomagnetic Effects in Shock-deformed Iron Alloys

By A. CHRISTOU
Materials Science Division, Naval Weapons Laboratory, Dahlgren, Virginia

[Received 25 November 1969 and in final form 6 April 1970]

ABSTRACT

The transverse magnetoresistivity of annealed and shock-deformed Fe, Fe-7·37 wt. % Mn and Fe-30 wt. % Ni was measured as a function of $\mathbf{B}/\rho_0$. The deformed material yields a curve which is in general shifted from the annealed metal. The shift in Fe is due to anisotropic scattering of conduction electrons by dislocations. In Fe–Ni and Fe–Mn the shift can be explained by a shock-induced second-order phase transformation occurring above 90 kbars.

§ 1. INTRODUCTION

RESISTIVITY and magnetoresistivity experiments render information on the effects of lattice defects on conduction electrons (Van Bueren 1967). Defects such as vacancies and interstitials are essentially isotropic scatterers, and will therefore diminish only the free path of the conduction electrons. It is well known that isotropic scattering centres reduce the absolute magnitude of the magnetoresistance, but their presence remains undetected in the Kohler diagram. Kohler (1938) has shown that if scattering of conduction electrons by the lattice can be described by a single isotropic relaxation time τ, then $\Delta\rho/\rho(0)$ will be a function of $H/\rho(0)$ only, where H is the applied field and $\rho(0)$ is the initial resistivity. Magnetoresistance measurements in alloys can provide information concerning the structures of Brillouin zones as well as transformations such as phase changes and precipitation from solid solution.

The Kohler curve is a characteristic of the metal and only by destroying the isotropy of τ are deviations from the Kohler curve obtained. The presence of anisotropic scatterers should show up in the magnetoresistivity of shock-deformed metals, since line defects have been generated with anisotropic strain fields around them (Cottrell 1953). The high density of dislocations is expected to result in a distortion of crystal symmetry. The effects of shock waves on the residual magnetic properties of iron have been investigated by Rose, Villere and Berger (1969). Kressel and Brown (1967) have studied changes in resistivity properties of shock-deformed metals. However, changes in magnetoresistivity characteristics have never been observed in shocked material.

Table 1. Chemical composition of materials investigated (wt. %)

	Mn	Ni	C	O	Cu	Quench temperature
Fe–Mn	7·37	0·0120	0·0015	—	—	900°c
Fe–Ni	—	30·0200	0·0014	0·030	0·010	850°c
Fe	—	0·0015	0·0014	0·025	0·031	—

Note : each metal was analysed for Si, Zr, B, Al, Sn, Nb, Co, Ti, Mo, V—all of which were undetected.

It is the purpose of the present investigation to report our magneto-resistivity studies of polycrystalline Fe, Fe–Mn and Fe–Ni. We have related our experimental results for pure Fe to anisotropic scattering due to the presence of dislocations. The results of Fe–Mn and Fe–Ni have been related to magnetic phase changes and the presence of a high density of dislocations. The alloys studied were prepared using electrolytic iron (99·9 + % purity) whose electrical resistivity at 14°K was found to be about 0·27 $\mu\Omega$-cm. The compositions of the metals studied with initial heat treatment are shown in table 1. It is emphasized that the heat treatment of the Fe–Mn and Fe–Ni alloys resulted in a two-phase structure (α and martensitic α') prior to shock loading. The increase of the total free energy due to shock loading at pressures between 90 and 150 kbars has induced a martensitic ($\alpha \rightarrow \epsilon$) transformation to take place.

§ 2. Experimental Details

The flying plate technique (Duval and Fowles 1963) was used in shock loading, allowing for both the magnitude and geometry of the pressure pulse to be controlled by the driver plate thickness. Table 2 contains the parameters of the shock-loading experiments. The specimens for galvanomagnetic measurements were in the form of thin rectangular samples 1 mm wide, spark cut from a thin foil 3 cm by 3 cm. Prior to shock loading the iron specimens were annealed for ½ hour at 600°C. This produced the desired grain diameter.

Table 2. Shock-loading parameters

Shock pressure (kbars)	Particle velocity (cm/sec)	Driver plate velocity (cm/sec)	Linear strain
90	0·024	0·048	0·0432
150	0·038	0·076	0·0454
300	0·077	0·145	0·0926
500	0·092	0·184	0·1159

The inductive method was used to measure the Hall coefficient. Chambers and Jones (1962) have provided the theoretical analysis of the method. The relation between the electric field E and the current J in the plane of an infinite sheet normal to the direction of B is :

$$E = (\rho + R_{\mathrm{H}}\mathbf{B}x)\mathbf{J}. \qquad (1)$$

The oscillatory magnetic field in the plane of the sheet obeys the equation :

$$\frac{d^2H}{dZ^2} = \frac{4\pi i\omega H}{\rho(1+iU)}, \qquad (2)$$

where

$$U = R_{\mathrm{H}}B/\rho. \qquad (3)$$

The resonant frequencies for forced oscillations corresponding to waves in a sheet of thickness b are :

$$\omega_{\mathrm{mr}} = \frac{m^2\pi|\rho(1+\omega)|}{4b^2}. \qquad (4)$$

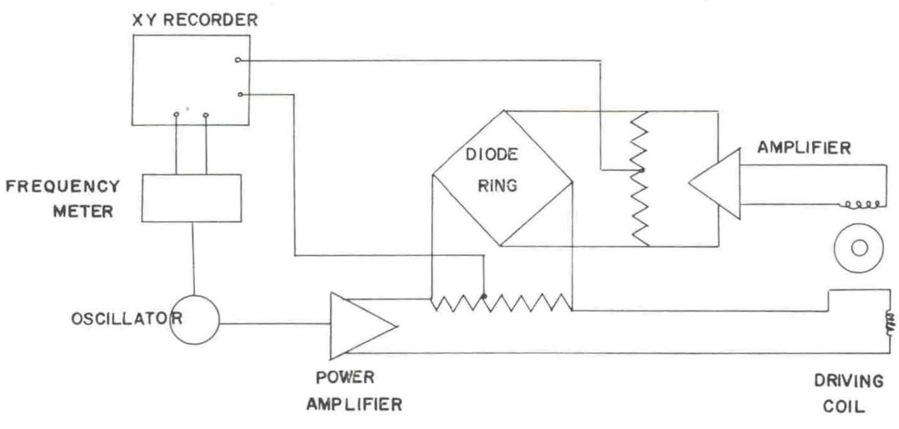
The Q of each resonance is :

$$Q = \frac{(1+u^2)}{2}. \qquad (5)$$

The resistivity ρ can be determined by measuring Q and substituting in eqn. (5).

The experimental system is shown in fig. 1, and is similar to the one used by Taylor, Merrill and Bowers (1963). Essentially a dispersion curve was obtained on the X–Y recorder from which ω_{mr} and Q can be obtained. The signal voltage and absorption curve is obtained by means of an RC circuit.

Fig. 1



Schematic diagram for measuring galvanometric properties by the inductive method.

§ 3. Results and Discussion

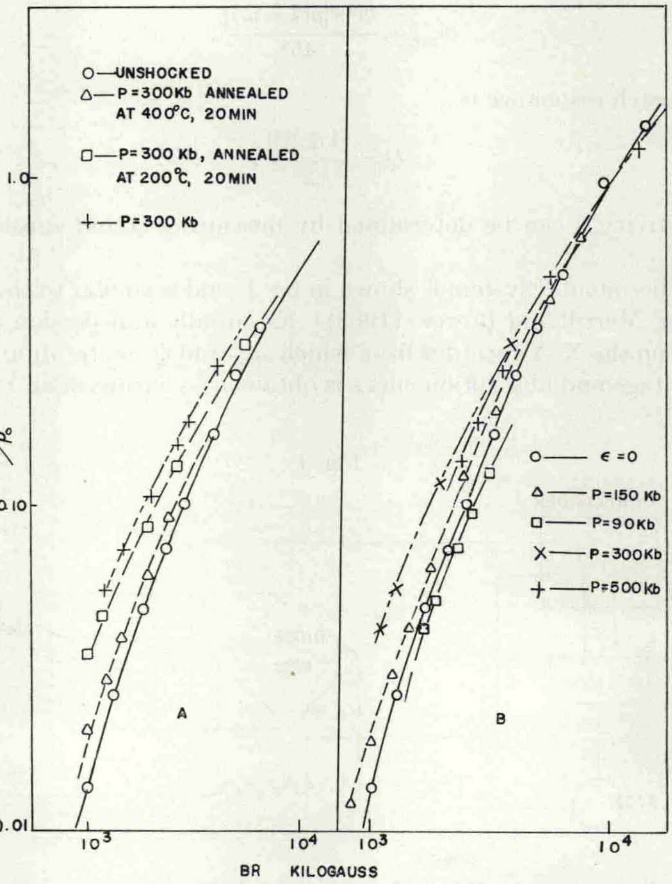
3.1. *Transverse Magnetoresistivity of Deformed Fe*

The increase of the normal resistivity at $B=0$ due to plastic deformation was measured for each Fe specimen as a function of linear strain. We found that $\Delta\rho=\epsilon^n$ with $n=1.6$. The magnetoresistivity was measured for each specimen as a function of

$$BR = B\,\frac{\rho^{RT}(0)}{\rho^{T,C}(0)} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

R is the resistivity ratio referred to room temperature, where the resistivity $\rho RT(0)$ is almost independent of c, the impurity level.

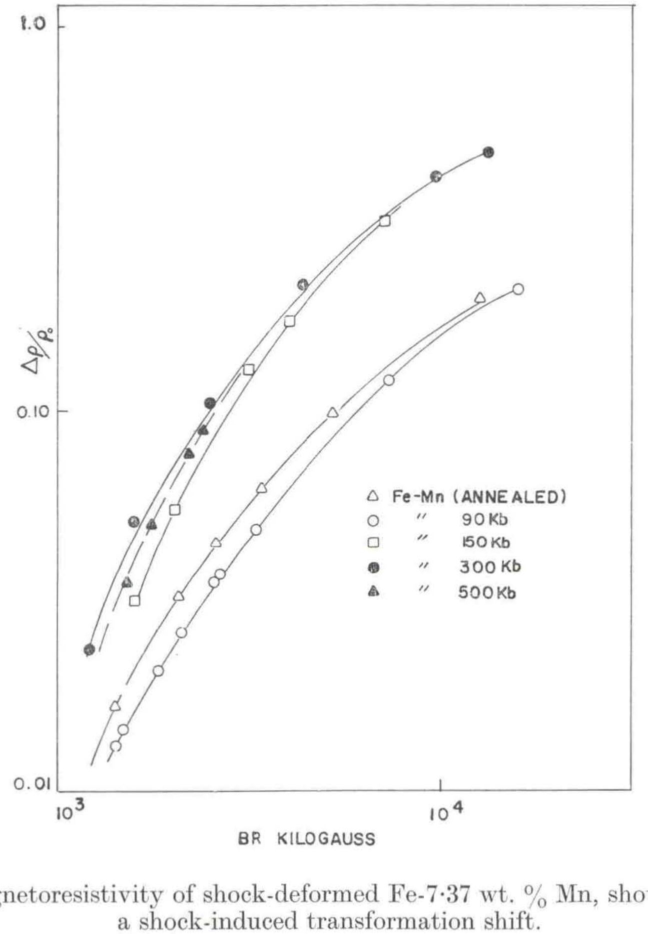
Fig. 2



Magnetoresistance of annealed and shock-deformed iron at 20°K. (*a*) Deformation shifts from the normal Kohler curve. (*b*) Recovery of the deformation shifts.

In the series of experiments on iron shown in fig. 2, it was found that at low BR strengths the shock deformation at 150–500 kbars caused an upward shift of the reduced Kohler curve. This shift increased with deformation, but decreased as BR approached 10^4 kilogauss. The negative shift of the 90 kbar specimens is the expected normal behaviour for shock deformation up to the 132 kbar magnetic transition point. The positive shift observed for pressures in the 150–500 kbar range denotes the modified behaviour attributed to the magnetic transformation. The 500 kbar deformation results in a smaller shift than that at 300 kbars. From electron microscopy studies it is evident that at 500 kbars the deformation process is competing with a recovery process induced by heating behind the shock wave. In fig. 2 (B), it is evident that annealing at 400°C produced a large negative shift towards the original position. At 600°C the curve returned

Fig. 3



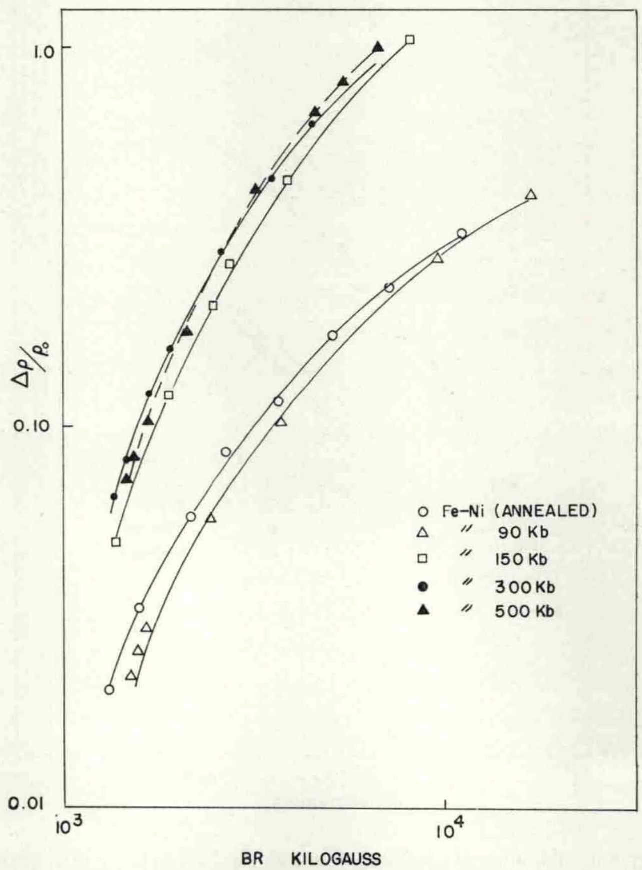
Magnetoresistivity of shock-deformed Fe-7·37 wt. % Mn, showing a shock-induced transformation shift.

to its original position. It is well known that the recovery of electrical resistance after plastic deformation occurs in various stages. The interpretation of these stages still presents difficulties, but investigators agree that stages II, III and IV are due to the migration and disappearance of point defects and stage V to the movement of dislocations. In shock-loaded material Kressel and Brown (1967) have situated stage V at 320–740° C. Consequently we conclude that the shift is totally suppressed only when dislocations are annealed out of the metal.

3.2. *Transverse Magnetoresistivity of Shock-deformed Fe–Mn and Fe–Ni*

The resistance changes in annealed and shock-deformed Fe–Mn and Fe–Ni were studied as a function of external magnetic induction. The results shown in figs. 3 and 4 indicate that in general two different values of magnetoresistivity can be obtained depending on the specimen's previous deformation history. The difference in $\Delta\rho/\rho_0$ due to the retained high

Fig. 4



Magnetoresistivity of shock-deformed Fe-30 wt. % Ni.

pressure of non-magnetic phase appeared evident at 150 kbars. The additional magnetoresistivity changes in the region of 150 to 500 kbars can be explained by the anisotropic scattering of conduction electrons by dislocations. The negative shift of the Kohler curve at 90 kbars is characteristic of ferromagnetic metals. The annealing data up to 750°C showed that the shift in $\Delta\rho/\rho_0$ could be recovered for specimens deformed between 150 and 500 kbars, and between 0 and 90 kbars. The 500 and 300 kbar Kohler curves shifted toward the 150 kbar curve, while the 90 kbar curve recovered toward the annealed material. The recovery effect in Fe–Mn and Fe–Ni, as in Fe, can be explained by the annealing out of dislocations. A second-order magnetic transformation has occurred above 90 kbars ; the residual effects cannot be annealed out since the recovery temperatures were maintained below the Curie temperatures.

In conclusion the transverse magnetoresistivity of annealed and of shock-deformed iron, plotted on a Kohler diagram, shows that the deformed material yields a curve which is in general shifted from that of the annealed metal. This shift can be explaned by considering the anisotropic scattering of conduction electrons by dislocations. The shift in shock-deformed Fe–Ni Fe–Mn alloys can be explained by a shock-induced second-order phase transformation occurring above 90 kbars.

Acknowledgments

The author acknowledges a Ford Foundation fellowship during the tenure of which the initial stages of this work was carried out. This work was also supported by the NWL Independent Research Program. Finally the author would like to thank Mr. D. Altman for his assistance during the experimental testing.

References

Chambers, R. G., and Jones, B. K., 1962, *Proc. R. Soc.* A, **270,** 417.
Cottrell, A. H., 1953, *Dislocations and Plastic Flow in Crystals* (Oxford).
Duval, G. E., and Fowles, G. R., 1963, *High Pressure Physics and Chemistry,* Vol. 2 (New York : Academic Press).
Kohler, M., 1938, *Phys. Z.*, **39,** 9.
Kressel, H., and Brown, N., 1967, *J. appl. Phys.*, **38,** 1618.
Rose, F., Villere, M., and Berger, T., 1969, *Phil. Mag.*, **18,** 1167.
Taylor, M. T., Merrill, J. R., and Bowers, R., 1963, *Phys. Rev.*, **129,** 2525.
Van Bueren, H. G., 1957, *Philips Res. Rep.*, **12,** 896.