The Magnetic Aftereffect in Iron After Shock Deformation

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It has been well known that the magnetization curve of a ferromagnet is not a static property, but is time dependent.[1] Snoek[2] initially showed that a carbon atom in bcc-Fe gives rise to this magnetic aftereffect. Although there exist other magnetic aftereffects,[3] as well, only the diffusion-controlled aftereffect will be considered in this paper. The delayed response to the applied magnetic field is due to the hindrance to domain wall motion created by interstitials whose energy depends on the direction of spontaneous magnetization of the surrounding lattice. The hindrance to domain wall motion is described as a stabilization by Néel.[4] The instantaneous response of domain walls to the applied field is decreased by interstitials in preferred sites with respect to the local orientation of the magnetization vector. The kinetics of the aftereffect can be described by a short-range interstitial diffusion which relaxes the stabilization.

In the present experiments, iron has been shock-deformed and magnetic aftereffects have been investigated at 300°K. This investigation was undertaken to determine how shock deformation alters the kinetics and magnitude of the aftereffect.

The iron specimens were plastically deformed by shock loading at pressures of 90, 150, 300, and 500 kbar. The samples of polycrystalline iron were in the form of elongated toroidal cores made up of one strip of 0.2 mm sheet. The field coil and pick-up coil were wound onto the iron core. The measurement technique was similar to that used by Tomono[5] and Rusnak *et al.*[6] and consisted of an electronically timed closure of a measurement circuit at specified time intervals after the application of a magnetic field. The flux change was measured from the time of circuit closure until zero flux change. Flux changes were detected on a galvanometer. The magnetic-field level was at 0.25 oe. Each specimen was demagnetized before a measurement was taken.

The aftereffect induction ΔB_α was measured as a function of time. The aftereffect induction is the difference between the magnetic induction at any time after field application, B_T, and the equilibrium induction B_e, after total relaxation. The total aftereffect induction ΔB_α^T is the difference between B_e and B_i, the instantaneous induction. The instantaneous induction is taken after complete eddy current decay.

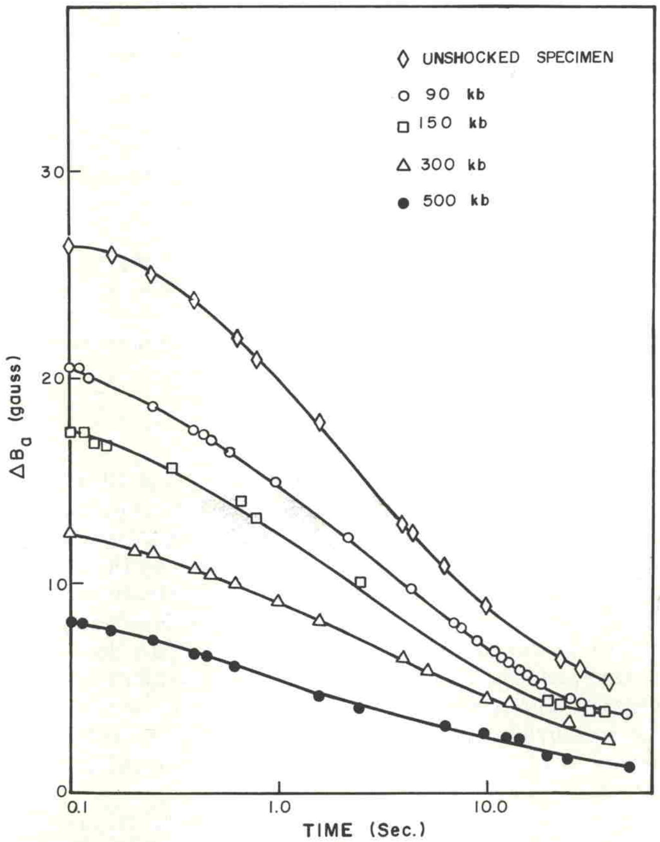

Fig. 1—The time dependence of the aftereffect induction after the application of a magnetic field. The total interstitial content was 65 ppm.

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In studying aftereffect kinetics ΔB_α is presented as a function of time, as shown in Fig. 1 for samples shock deformed up to 500 kbar. The aftereffect induction was found to decrease with increasing shock deformation. To determine if the kinetics of the aftereffect is altered by dynamic prestrain, a plot of the ratio of the aftereffect induction to the total aftereffect induction $\Delta B_\alpha/\Delta B_\alpha^T$ vs time was made for annealed and shock-deformed specimens. It was found that the $\Delta B_\alpha/\Delta B_\alpha^T$ vs time curve was not changed by shock deformation. Therefore, the kinetics of the aftereffect was not altered by shock deformation. A similar observation was made by Rusnak *et al.*[6] who found that the magnitude of the aftereffect decreased after a plastic prestrain treatment, without altering the kinetics.

The total aftereffect induction ΔB_α^T was found to vary experimentally with dynamic prestrain according to:

$$\frac{1}{\Delta B_\alpha^T} = k_1 + k_2 \epsilon_s^n, \quad n = 0.4 \qquad [1]$$

where ϵ_s is the total transient shear stress the specimen experienced in shock deformation. The total transient shear strain was calculated, assuming uniaxial deformation, from the following equation:[7]

$$\epsilon_s = \frac{4}{3} \ln \frac{V}{V_0} \qquad [2]$$

where V_0 and V are the specific volumes of the material in the initial and compressed states respectively. The values of specific volume V as a function of applied pressure were obtained from the data of McQueen and Marsh.[8] The constants k_1 and k_2 depend on the interstitial content of iron, and were found to have a value of 0.12 and 0.15, respectively, for a probable interstitial content of 65 ppm (carbon and nitrogen).

The magnetic hardness for samples after shock deformation was measured in order to determine the effect of lattice defects on domain wall movement. Magnetic hardness was determined by the slope of the magnetization curve dB/dH at the same field level at which the aftereffect was measured. An increase in the magnetic hardness means a decrease in dB/dH. In addition, an increase in magnetic hardness implies an increase in the stabilization-independent resistance to domain wall motion. The amplitude of the magnetic relaxation is related to the concentration C of defects and to the gradient of the domain wall energy:

$$\frac{1}{\mu(t=\infty)} - \frac{1}{\mu(t=0)} = C\frac{dE}{dX} \qquad [3]$$

where μ is the initial permeability before and after relaxation.[9] Since the magnetic induction is proportional to permeability, the aftereffect induction is proportional to dB/dH if shock deformation only increases the magnetic hardness of the material. Fig. 2 illustrates that this was the case with shock-loaded iron. It is noted that for increasing prestrain condition, dB/dH decreases, and the induction level B at $H = 0.25$ oe decreases. The induction level B at which the aftereffect was measured varied from 141 G for the annealed sample to 21 G for the sample with 500 kbar deformation.

The value of the fictitious aftereffect field[6] H_F, is given by the slope of the curve in Fig. 2, ($\Delta B_\alpha^T = H_F dB/dH$). H_F is therefore a measure of the stabilization force of the interstitials. The magnitude of the fictitious field is 0.024 oe. This agrees in magnitude with the stabilization field of Brissonneau[10] and Rusnak and Cullity.[6] Therefore, H_F measures the stabilizing effect of interstitials on domain walls, which is deformation independent.

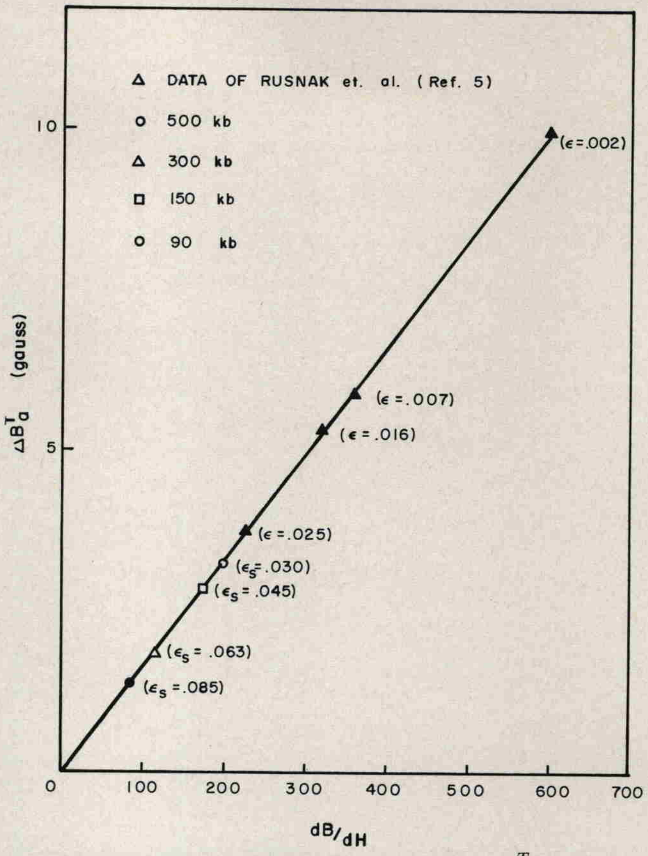

Fig. 2—Variation of total aftereffect induction ΔB_α^T with dB/dH. The samples had various amounts of shock deformation.

The decrease in the magnitude of the aftereffect with shock deformation is probably not the result of the decrease in the stabilization force of the interstitials. However, the reduction in the aftereffect induction may be accounted for by an increased hindrance to domain wall motion produced by shock-generated lattice defects and stress concentration points which are stabilization independent.

The investigation of Rusnak *et al.*[6] in the low strain region (0 to 0.038) reached the same conclusions as the present investigation in the large deformation, high strain rate region (true plastic strain up to 0.085). Therefore, it is concluded that for plastic strains up to 0.085 and for strain rates up to 10^5 per sec, (approximate strain rate for dynamic loading), deformation does not decrease the stabilization force of the interstitials.

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