Phil Mag., 21, 203-5 (1970)

r the obstacle radius
neter y of the present
e radius R^* of their

. . . . . . (25)

pplied stress. From
k-hardening in stage

. . . . . . (26)

. . . . . . (27)

l screw dislocations;
screw dislocations;
e for θ_{II}. A closer
any approximations
n this way may be
en replaced by the
t k_1 is found to be
up, that the obstacle
and that for screw
ons.

p and assistance of
is paper.

N., 1951, *Phil. Mag.*,

439.
. **45**, 663.

(Groningen, Holland:

ys., **36**, 1927.

CORRESPONDENCE

Susceptibility and Saturation Magnetization Measurements in Shock-loaded Iron Manganese

By A. Christou

School of Metallurgy and Materials Science, University of Pennsylvania, Philadelphia, Pa.†

[Received 23 July 1969 and after revision 7 October 1969]

Abstract

It is shown that shock waves at pressures of 90, 150, 300 kbars have a notable effect on the magnetic properties of FeMn (92·4/7·6 wt. %). In increasing fields (up to 30 kilo-oersteds) three regions including the Barkhausen effect have been identified. The reduction in magnetization ΔM produced by shock loading can be represented by $\Delta M = q/H + p/H^2$, where q depends on the applied stress. In addition, susceptibility measurements indicate a shock-induced Curie transformation.

Work-hardening and the existence of high densities of dislocations have a notable effect on properties of magnetic materials. Studies by Kronmüller (1959) and Friedel (1956) have related the reduction in magnetization to plastic deformation. Dektyar and Levina (1962) have explained the increase of the critical field H_c with work-hardening. The effects of shock waves on the residual magnetic properties of armco iron have been investigated by Rose, Villere and Berger (1969). However, changes in saturation magnetization and susceptibility have never been observed in shocked material.

It is the purpose of this correspondence to report the results of our magnetization and susceptibility studies in shock-loaded FeMn (92·4/7·6 wt. %). We have related our experimental results to the effect of work-hardening and magnetic transformations.

Proper heat treatment of the alloy FeMn 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 transformation ($\alpha \rightarrow \epsilon$), and has caused a demagnetization transition to take place. We were not able to determine the exact pressure of the transformation, but we believe this pressure to be about 110 kbars. Density measurements of the shock-loaded specimens clearly indicate that the high pressure phase has been retained. A density change of 3·79% has been measured for specimens shocked at 150 and 300 kbars.

† Present address: Materials Science Division, U.S. Naval Weapons Laboratory, Dahlgren, Va.

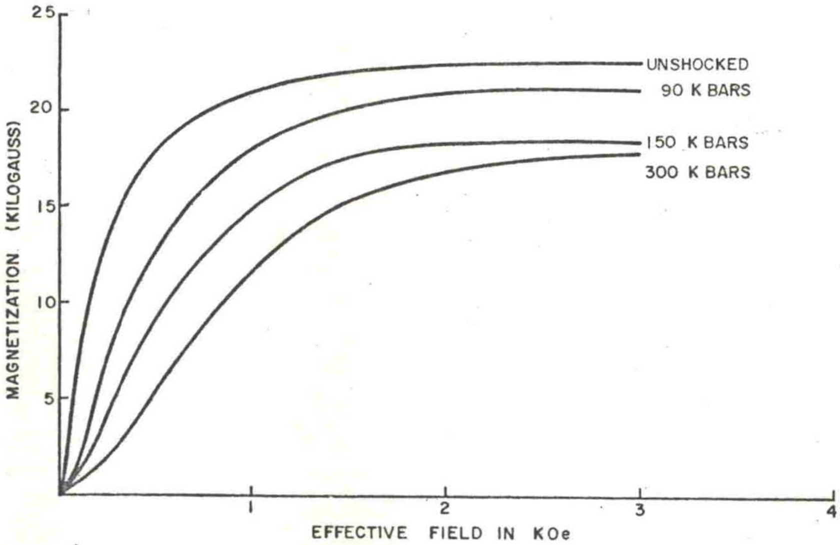
Consequently, the changes in saturation magnetization and susceptibility that were measured reflect both the work-hardening effects and the occurrence of a crystallographic phase transformation.

Magnetization and susceptibility were measured by means of a magnetic balance after the design of Sucksmith and Thompson (1954). The field gradient, which is independent of the applied field, was supplied by two brass strips. This method allowed for the passage of 65 amps through the brass strips. The results of these experiments appearing in the table

Peak pressure (kbars)	Susceptibility $1/\chi \times 10^{-3}$	Saturation induction (kilogauss)
90	6·32	21·5
150	22·67	18·6
300	21·39	18·1
Annealed	4·69	22·1

clearly indicate a variation in susceptibility between the specimens shock loaded at 90 kbars and those at 150 and 300 kbars. The values for $1/\chi$ of $6{\cdot}32 \times 10^3$ at 90 kbars and $22{\cdot}67 \times 10^3$ at 150 kbars generally follow the Curie–Weiss law, indicating a magnetic transformation. The transformation, unlike those of the ordinary type which take hours for completion, occurs martensitically.

The magnetization curves appearing in the figure indicate different approaches to saturation for each pressure, and in general a lowering of magnetization M observed under a field H. Three distinct magnetization regions are shown. There is an initial increase in M, with slope dM/dH



Magnetization curves for iron manganese shock loaded up to 300 kbars.

which is definitely smaller than in the fully annealed state. There is then a rapid increase in magnetization known as the Barkhausen effect, and finally the approach to saturation occurs at higher fields than in the fully annealed state. In the large field range, the reduction in magnetization produced by work-hardening can be represented by:

$$\Delta M = \frac{q}{H} + \frac{p}{H^2},$$

where p and q are constants. This relationship holds in the stage of rapid hardening. We believe that during the initial stages of work-hardening the term q/H is associated with the work-hardening of dislocation dipoles. Once work-hardening dominates, however, the first term is connected with the relaxation of piled-up groups.

It is generally known that at low fields and in well-annealed polycrystals with large grains, Bloch walls are made mobile under the applied field. In worked material, under very small fields, the walls are able to bend between their pinning points, giving rise to the initial permeability. Above a critical field H_c the walls escape from their pinning point and move irreversibly, giving rise to the Barkhausen jump. The large number of piled-up groups of dislocations introduced by shock loading provides at least some of the pinning points. The pinning energy per unit length of dislocation is of the order of $\lambda\sigma\delta^2 \simeq \lambda\mu b\delta$, where λ is the magnetostriction, δ is the width of the Bloch wall, μ is the shear modulus and b is the interatomic distance. The average stress σ is computed in a cylinder of diameter δ around the dislocation. H_c is obtained by equating this energy to $H_c M_s S\delta$ which is the energy gained from H_c when a length $2S$ of Bloch wall moves forward by δ. Therefore

$$H_c \simeq \frac{\lambda\mu b}{S} M_s.$$

The above equation explains the order of magnitude of the initial permeability of the Barkhausen effect (Dektyar and Levina 1962).

Hence, we have identified three regions of magnetization, each of which has been related to the metal's dislocation and domain sub-structure. The increase in susceptibility is due to a shock-induced magnetic transition.

Acknowledgments

The author wishes to express his gratitude to Professor Norman Brown and to Dr. F. I. Grace for his interest in the problem and for his assistance in the experimentation. The author also acknowledges a Ford Foundation fellowship and ARPA support during the tenure of which this investigation was carried out.

References

Dektyar, I. Ya., and Levina, D. A., 1962, *Physics Metals Metallogr., N.Y.*, **12**, 27.
Friedel, J., 1956, *Phil. Mag.*, **46**, 514, 1169.
Kronmüller, H., 1959, *Z. Phys.*, **154**, 574.
Rose, M. F., Villere, M. P., and Berger, T. L., 1969, *Phil. Mag.*, **19**, 39.
Sucksmith, W., and Thompson, J. E., 1954, *Proc. R. Soc.* A, **225**, 326.