Studies on Piezo-Magnetization (III) —PRM and Relating Phenomena—

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(Received March 25; revised April 30, 1968)

Abstract

Irreversible changes of the remanent magnetization of fine grains of ferromagnetics under uniaxial compression have been experimentally examined in a systematic way. The compression of a sample in a magnetic field results in a remanent magnetization which is greater than that obtained without compression in the same field. The pressure remanent magnetization PRM produced by removing uniaxial compression in a magnetic field increases with increasing compressional stress. The dependence of the PRM of a fine grain assemblage of titanomagnetite upon pressure P and a magnetic field H_{ex} can be expressed by $a \cdot f(p) \cdot H_{ex}$, where $f(p)$ increases monotonically with respect to pressure, reaching some limiting value at pressures higher than 2 kb, and a is a numerical constant systematically dependent on grain size. The ratio of PRM/IRM in a weak magnetic field for homogeneous bulk specimens with grain size larger than about 0.1 mm varies from 1 to 5, whereas specimens containing fine grains with diameters less than 0.1 microns have ratios of 20 to 40. A similar grain size dependence is found for Cu-Co superprecipitates containing homogeneously dispersed ferromagnetic fine grains in a non-ferromagnetic matrix. Stability of the PRM of a fine grain assemblage of titanomagnetite has been examined through ac field demagnetization. The decay of PRM with respect to increasing peak intensity of an ac field resembles that of IRM rather than that of ARM.

The intensity of various types of remanent magnetization, such as TRM, IRM and ARM, decreases irreversibly as the specimen is compressed uniaxially in a non-magnetic space. The observed hyperbolic decay of remanent magnetization with increasing compressional stress can be accounted for by a PRM induced by the demagnetizing field of the specimen itself in a reverse sense to the initial remanent magnetization. It is shown that the PRM vector deviates from the direction of an external magnetic field toward a plane perpendicular to the compressional axis when the magnetic field is not parallel or perpendicular to the axis of compression. The maximum deflection angle is calculated to be 10 degrees and occurs when the angle between the magnetic field and the compressional axis is about 45 degrees.

The mechanism of acquisition of PRM is briefly discussed. A more detailed discussion of the problem will be given in a future paper.

1. Introduction

The term Piezo-Remanent Magnetization (PRM) was first defined by *Domen* (1962) as the isothermal remanent magnetization acquired by a ferromagnetic as a result of the application and subsequent release of an axial stress in the presence of an external magnetic field. The phenomenon was systematically studied by *Domen* for an assemblage of

fine grains of magnetite using a uniaxial press capable of up to ca. 10 kb of pressure. According to *Domen*, PRM increases with increasing pressure and asymptotically reaches some limiting value which is dependent on ambient temperature and on grain size of the specimen. Acquisition of PRM can be understood as resulting from an irreversible process caused by an inverse magnetostriction effect (*Chikazumi* and *Suzuki*, 1955). Such irreversible inverse magnetostriction effects have been studied experimentally by *Nagaoka* (1889) for nickel, by *Honda* and *Terada* (1907) for iron, by *Buckley* and *McKeehan* (1925) for 68-permalloy, by *Williams*, *Bozorth* and *Shockley* (1949) for iron-silicon alloy and by *Grabovskii* and *Parkhomenkho* (1953) for natural iron oxides. However, the detailed mechanism by which a uniaxial stress produces an irreversible change of magnetization has not yet been clarified.

The reversible change in magnetization caused by uniaxial stress has been studied experimentally by *Honda* and *Terada* (1907) for nickel and steel wires, by *Carmichael* and *Fuller* (1967) for nickel rods, by *Kapitza* (1955) for volcanic rocks, and by *Grabovskii* and *Parkhomenkho* (1953) and *Nagata* and *Kinoshita* (part I, 1965) for magnetite and titaniferous magnetites. The initial susceptibility of an assemblage of titanomagnetite grains under compression decreases hyperbolically with an increase in uniaxial compressional stress p , according to $\chi = \chi_0 / (1 - \beta \cdot p)$, and increases under tension $-p$ in the same way, where χ_0 is the initial susceptibility at $p=0$. This has been interpreted by *Kern* (1961), *Stacey* (1962) and *Nagata* (1966) for an assemblage of single domain particles, and by *Kinoshita* (part II, 1963) for a semi-multidomain system, as being due to an increase in the magnetoelastic energy which acts as a restoring force against the magnetostatic energy of the external magnetic field.

Both the present experiments and work described in a previous paper (*Nagata* and *Kinoshita*, 1965) aim at resolving the apparent conflict between the decrease of initial susceptibility and the increase of PRM with increasing pressure, and at understanding the mechanism by which PRM is acquired under uniaxial compression.

2. Method of measurement

In the present experiments, a piston anvil of a press and high-pressure vessel were, respectively, made of non-magnetic stainless steel and beryllium-copper alloy. End of the press anvil which comes in contact with the specimen was a cylindrically shaped corundum chip with a diameter of 10 mm, sintered at high pressure and high temperature. The pressure exerted by the press was measured by means of a manometer type Bourdon tube gauge (0–5 kb). A side view of the apparatus is shown in a previous paper (*Nagata* and *Kinoshita*, p123, 1965). An external magnetic field was exerted on the specimen by a solenoid or a Helmholtz coil. Remanent magnetization of samples was measured by means of an astatic magnetometer. Magnetization of the specimen in the presence of both pressure and magnetic field was measured with a ballistic magnetometer as described in a previous paper (*Nagata* and *Kinoshita*, 1965).

The absolute pressure was calibrated through the first order transition with respect to

volume of pure NH_4F powder at 3.7 kb of pressure (Swenson and Tedeshi, 1964). A test piece of NH_4F was packed in a high-pressure vessel of the same form as was used in previous experiments. The volume change with compression was detected by measuring the distance between piston anvils with a micrometer. The pressure calibration curves are shown in Fig. 1, where the abscissa represents the pressure on a specimen calculated purely geometricaly from the ratio of cross sections of the piston anvil and the specimen. For two specimens of different dimensions, 3.7 and 3.8 kb were read on a pressure gauge as averaged transition pressure. Though some friction must exist between the vessel and the anvil, the accuracy of the Bourdon tube gauge used was within 5%.

Compression of a loosely packed assemblage of fine grains of ferromagnetics may result in an irreversible reduction of the bulk volume of the specimen accompanied by the pulverization of grains to a smaller size. Moreover, it seems likely that the volume reduction with pulverization of grains under compression is inevitably accompanied by movement or rotation of individual grains of the specimen. If the specimen initially has some remanent magnetization, its bulk magnetization

must change in intensity and direction owing to the movement and pulverization of the individual magnetized grains under compression. In addition to this effect, the pulverization of grains must result in an increase in coercive force, and a decrease in magnetic susceptibility of the specimen. Thus, the effect of uniaxial compression of an assemblage of brittle grains is not to cause an intrinsic change in the magnetic properties of the material but to cause a change both in shape and size of individual grains of a specimen. It was shown that these spurious effects can be eliminated by repeated compression of the specimen. After about three compressions up to 4 kb, no further pulverization of the specimen grains was observed. The results of preliminary experiments, testing the pulverization effect, are shown in Fig. 2 as a function of applied pressure p , where the "pulverization ratio" plotted on the ordinate is defined as a ratio of a mass of grains pulverized into zero to 70 microns of diameter to the total initial mass of the specimen with diameters of 200

Fig. 1 Pressure calibration using an assemblage of fine crystals of NH_4F packed in a cylindrical vessel. The first-order volume transition occurs at 3.7 kb. Pressure on the abscissa is calculated geometrically from ratio of cross sections of a press anvil and a specimen. Averaged transition pressure read on a pressure gauge is shown with thick bars. Arrows indicate paths of hysteresis curves of the $-\Delta V$ versus pressure relation. Upper curves are for specimen with a diameter of 10 mm and thickness of 7 mm and lower curves for a 10 mm diameter and 5 mm in length.

Fig. 2 Pulverization of magnetite grains due to axial compressional stress. The ordinate represents the mass ratio of grains pulverized into smaller size (less than 70 microns) to the total weight of the initial sample grains (200–250 microns). Assigned numbers indicate 1, 5 and 7 repeated compressions.

to 250 microns. In the following experiments, therefore, specimens were usually prepared by preliminary compression up to 4 kb repeated more than ten times in non-magnetic space before magnetic measurement.

3. Piezo-Remanent Magnetization of titanomagnetite fine grains

A piezo-remanent magnetization was produced by compression of loosely packed fine grains of titanomagnetite which had initially been demagnetized by an ac field of 570 Oe peak. Repeating the same procedure of PRM production and subsequent ac demagnetization, up to four successive PRM's were obtained, as shown in Fig. 3. The intensity of PRM obtained by compression decreases with repetition, rapidly reaching an limiting value after several compressions. The difference between the second and fourth curves of PRM versus pressure is comparable to the possible experimental error, indicated by a heavy cross in the figure, and may not be significant. Thus, ten times of compression up to 4 kb previous to magnetic measurements are sufficient to stabilize magnetically a specimen composed of fine grains of titanomagnetite.

Dependence of the PRM intensity of an assemblage of fine titanomagnetite grains (grain size less than 70 microns) upon pressure and intensity of external magnetic field are illustrated in Figs. 4 and 5, respectively. The axis of uniaxial compression is parallel to the direction of the external magnetic field and, hence, the resultant PRM always points exactly in the same direction as that of the external magnetic field. The main characteristics of PRM of an assemblage of fine grains of titanomagnetite are summarized as follows:

- i) The intensity of PRM increases monotonically with increasing pressure up to 4 kb.
- ii) The intensity of PRM is proportional to the intensity of an external magnetic field less than 100 Oe.

Therefore, the dependence of PRM upon pressure and magnetic field can be expressed by

$$J_{pr} = a \cdot H_{ex} \cdot f(p) \quad (3-1)$$

where a , H_{ex} and $f(p)$ denote a constant of proportionality, external magnetic field and a hyperbolic function of p to be fitted to the experimental curves of PRM versus pressure, respectively.

Fig. 3 PRM versus pressure relation of an assemblage of fine grains of natural titanomagnetite. Curves 1 to 4 represent PRM's acquired by successive compressions up to fourth time. Sample of titanomagnetite, initial grain size smaller than 70 microns. Pressure axis is parallel to the magnetic field of 50 Oe.

Fig. 4 PRM versus pressure relation of an assemblage of fine grains of titanomagnetite. PRM was acquired in the initial compression in the same way as for curve 1 in Fig. 3. External magnetic field (H_{ex}) is parallel to the axis of compression, given as a parameter on each curve.

A similar relation of PRM versus pressure was observed not only for an assemblage of magnetite fine grains packed in a cylindrical shape but also for fine magnetite grains packed between pyrophyllite sheets in a form of thin circular disk of 10 mm diameter and 2 mm thickness, a bulk crystal of titanomagnetite in a shape of cylinder and a mixture of fine magnetite grains (less than 0.1 microns in diameter) and non-magnetic pyrophyllite powder showed similar behavior. The results are shown in Fig. 6, where the ordinate is given in an arbitrary unit. From the figure, it is concluded that no significant difference exists in PRM versus pressure among these different types of specimen, suggesting that the main configuration of the stress patterns in individual grains is similar for these three specimens.

PRM effect is also observed in cobalt and nickel chips (both, purity 99.9%). Figs. 7 and 8 show the PRM of cobalt and nickel chips which have been previously annealed at 800°C for 30 minutes in air to release residual stress caused by chipping. The specimen was compressed up to 4 kb in a magnetic field, and subsequently demagnetized by an ac field. Repeating the same procedure, successive PRM versus pressure curves were obtained (curves 1, 2 or 3 and 5), similar to the above case of fine grains of titanomagnetite. Obviously, some residual stress remains due to friction between specimen and high-pressure

Fig. 5 PRM versus external magnetic field. Pressure, in units of kb, is given as a parameter on each curve. The sample and other conditions are the same as in Fig. 4.

Fig. 6 PRM induced in three types of specimen to check distribution of stress in individual grains of specimen under compression. Samples; **a**: Synthetic twin crystal of $0.8\text{Fe}_3\text{O}_4-0.2\text{Fe}_2\text{TiO}_4$, 10mm in diameter and 10 mm in length. **b**: Fine grained magnetite dispersed in a non-magnetic matrix of pyrophyllite powder. **c**: An assemblage of fine grains of titanomagnetite packed in a thin disk-shaped space, 10 mm in diameter and 2 mm in thickness.

Fig. 7 PRM in cobalt chips. Compression up to 4 kb was repeated 5 times (curves 1 to 5). The specimen was previously annealed in air at 800°C for ca. 30 minutes. Pressure axis is parallel to the magnetic field of 500 Oe.

Fig. 8 PRM in nickel chips. Compression up to 4 kb was repeated 5 times (curves 1 to 5). The condition is the same as in Fig. 7.

vessel even after the complete removal of external stress, which, in turn, affects the configuration of the PRM versus pressure relations.

PRM of an assemblage of fine grains of titanomagnetite was subject to ac field demagnetization in a non-magnetic space. Demagnetization were carried out in an ac field of 50 Hz with a maximum intensity of 300 Oe peak. Results are illustrated in Fig. 9, with an example for ARM given for comparison. Obviously, PRM decays more rapidly with increasing ac field than ARM.

4. Effect of grain size on PRM

4-1 PRM of titanomagnetites

The intensity of PRM is strongly dependent on the average grain size of a fine grained specimen. Summarizing the results obtained in the present study for PRM of titanomagnetites, the grain size dependence of PRM is listed in Table 1, where the efficiency of PRM production is expressed by the ratio of PRM to IRM induced in the same magnetic field. A similar result has been obtained by *Domen* (1962) for fine grain assemblages of natural magnetite.

Table 1. Grain size dependence of PRM. All the data for assemblages of titanomagnetite with a TiO_2 content of less than 10 wt% are included here.

specimen size in microns	homogeneous single cryst. 10^4	sintered poly cryst. 10^3	powdered sam- ple ca. 200	ca. " 70	0.1-"0.01
PRM/IRM	1-2	4-5	3-4	4-5	20-40

4-2 PRM of Cu-Co superprecipitates

PRM of fine grains of ferromagnetics homogeneously dispersed in a non-magnetic matrix was examined for copper-cobalt superprecipitates. The chemical and magnetic properties of the alloy are well known (*Kobayashi*, 1962). In the alloy, cobalt is soluble only to the extent of 5 wt% at 1000°C, 3 wt% at 940°C and 0.3 wt% at 400°C. It is, therefore, possible to obtain fine grains of ferromagnetic superprecipitates of f.c.c. structure containing ca. 10 wt% of copper in the non-ferromagnetic copper matrix if the homogeneous ingot of alloy containing more than 2 wt% of cobalt is aged at 750°C. Alloy specimens were made from copper chips of 99% purity and electrolytic cobalt powder of 99.9% purity. Cobalt (2 wt%) and copper were mixed and fused in vacuum of about 10^{-4} mmHg sealed in a quartz tube and the ingot was homogenized by heating at 1150°C, just below the melting point,

Fig. 9 The ac field demagnetization of IRM (50 Oe), PRM (50 Oe, 1 and 4 kb) and ARM ($H=800$ Oe, $h=10$ Oe). The result given for ARM is reproduced from Rimbert's experiment. Samples are assemblages of fine grains of titanomagnetite.

for about 50 hours, and subsequently quenched into water by crushing the sealed tube. The alloy ingot was then cut into disks of 10 mm in diameter and 5 mm in thickness.

In aging, the specimen was again sealed in an evacuated quartz tube and put in an electric furnace after the temperature in the automatically control furnace had settled at 750°C. Then the specimen was aged at constant temperature for a specific time interval. Electron-microscopic photographs of the superprecipitates of f.c.c. Cu-Co alloy in a paramagnetic copper matrix were thoroughly studied by *Phillips* (1965). The composition and heat treatment of the specimen in the present experiment are the same as that of the specimen prepared by *Phillips*. According to the author, fine grained crystals of superprecipitate with nearly equal diameters less than 0.001 microns became visible in a few tens of seconds by aging at 750°C. The diameters of the crystal increase gradually, and exceed 0.1 micron after one week of aging at a constant temperature. The magnetic properties of the superprecipitates has been studied in detail by *Kobayashi* (1962), and magneto-mechanical effects by *Tamagawa* and *Mitui* (1965).

Results of the present experiments are shown in Fig. 10, where the time interval of aging is plotted on the abscissa in units of minutes with a logarithmic scale, and relative values of the magnetization on the ordinate with an arbitrary unit. In the figure, $J = \chi \cdot H$, PRM (143 Oe, 3 kb), PRM (28 Oe, 3 kb), VRM (relaxation in magnetization) and IPM denote, respectively, reversible magnetization induced in an external magnetic field of 20 Oe, PRM produced by compression at 3 kb in magnetic fields of 143 and 28 Oe, after-effect of PRM

Fig. 10 Change in the magnetic properties of Cu-Co alloy with respect to aging. $J = \chi \cdot H$: Reversible magnetization in a 20 Oe dc field. IRM: Remanent magnetization induced by a 20 Oe dc field. PRM (143 Oe, 3 kb) and (28 Oe, 3 kb): PRM's produced by compression of 3 kb in a magnetic field of 143 Oe and 28 Oe. VRM: After-effect of remanent magnetization 15 minutes after release of both stress and magnetic field.

and IRM 15 minutes after release both of an external magnetic field and compressional stress and isothermal remanent magnetization induced by a 20 Oe dc field. The change in IRM and J with aging is in good agreement with the results of *Kobayashi* (1962). It is striking that the peak intensity in the PRM falls nearly in the same aging period as that of IRM. PRM versus pressure relations are shown in Fig. 11, in which the figure on the left shows the change in intensity of IRM of the specimen magnetized up to a specific magnetic field (A to D). A bent is seen in the magnetization curves at about 60 Oe which indicates a homogeneous distribution of fine crystals of superprecipitates with nearly equal diameters in an aged alloy. No distinct difference was found among

PRM versus pressure relations for cases A to D in the figure. The ac field demagnetizations of the PRM and IRM are shown in Fig. 12. We do not find, again, any distinct difference between decay modes for IRM and PRM with respect to ac field demagnetization.

Though the PRM versus pressure relation of the superprecipitate is simple, serious difficulties in explanation of the effect of pressure on the magnetization of Cu-Co alloy arise from a large plastic deformation of the alloy under axial compression. Plastic flow may have occurred even though the specimen was held tightly in a high-pressure vessel and,

Fig. 11 Left figure shows IRM versus magnetic field for Cu-Co alloy. In the right figure, PRM is induced by various specific intensities of external magnetic field (A to D). The sample is a cylindrically shaped Cu-Co alloy aged for 20 minutes. The axis of compression and the magnetic field are parallel to each other.

Fig. 12 The ac field demagnetization of IRM and PRM of Cu-Co alloys. Left; aged for 6 minutes. a: PRM (117 Oe, 3 kb). b: PRM (57 Oe, 3 kb). c: IRM (240 Oe). Right; aged for 30 minutes. a: PRM (143 Oe, 3 kb). b: PRM (29 Oe, 4 kb). c: IRM (228 Oe).

hence, such a deformation must accompany a remanent flow texture resulting in an induction of some kind of axial magnetic anisotropy affecting the intensity of remanent magnetization of the alloy as reported by *Tamagawa* and *Mitui* (1965). However, it is concluded that PRM is most effectively induced in superprecipitated crystals of Cu-Co alloy, aged for about 20 minutes at 750°C, that corresponds to ferromagnetic superprecipitates with a mean diameter favorable to a single (or semi-single) domain structure in a non-ferromagnetic matrix, as mentioned by *Kobayashi* (1962).

5. Relating phenomena of PRM

5-1 Pressure demagnetization of remanent magnetization

Changes in the remanent magnetization with axial compressional stress were measured for assemblages of fine grains of titanomagnetite with two different average grain sizes (150–250 and 10–50 microns), nickel chips, cobalt chips, a cobalt cylinder and a basaltic rock. Using the previous notations (*Nagata* and *Kinoshita*, p128, 1965), the measured quantity is expressed as J_r (H+, HO, P+, PO). The results are shown in Figs. 15 and 16 where $(J_r)_p^{H_{ex}=0}$ denotes the resultant remanent magnetization of a specimen which remained after release of pressure p in a non-magnetic space $H_{ex}=0$, with initial remanent magnetization

Fig. 13 Pressure demagnetization of various types of remanent magnetization uniaxially compressed in a non-magnetic space, measured after release of compression. Samples and initial remanent magnetization are:

a: Fine grains of titanomagnetite of natural origin (grain sizes, 200 to 250 microns). IRM induced in 50 Oe.

b: The same as a (grain sizes less than 70 microns). IRM induced in 50 Oe.

c: Cobalt metal in a disk shape. Saturated IRM induced in ca. 5000 Oe.

d: Cobalt chips. ARM induced in an exciting field of 230 Oe superposed on a 5 Oe dc field.

e: Nickel chips. ARM induced as in d.

The direction of magnetization in all cases except c is parallel to the axis of compression. In c, the former is perpendicular to the latter.

Fig. 14 Pressure demagnetization accompanied by ac field demagnetization. An ac field demagnetization of the same initial remanent magnetization (TRM) is shown with full circles for comparison. The TRM was induced in a 6 Oe dc field. Samples are basaltic rocks from lava on the Ohshima Island.

J_r . The initial remanent magnetizations have different origins, such as in Fig. 13, the IRM of fine grains of magnetite, saturated IRM for a cobalt disk and ARM induced by a 230 Oe ac field superposed on a 5 Oe dc biasing field for cobalt and nickel chips, and in Fig. 14, the TRM of a basaltic rock induced in a 6 Oe dc field. In the latter figure, the decay of TRM with respect to ac field demagnetization for the same rock specimen is shown for comparison with that of the pressure demagnetization. In all cases except the saturated IRM (J_{rs}) of a cobalt disk, the direction of magnetization was parallel to that of compression axis, whereas the J_{rs} of a cobalt disk was set perpendicular to the latter.

The decay of remanent magnetization due to axial compressional stress may be interpreted as the result of an inverse effect of PRM in the presence of a demagnetizing field in a specimen. Empirically, the intensity of PRM is expressed by (3-1). Then replacing H_{ex} with the demagnetizing field $-NJ_r$ of the specimen, the rate of decay of the remanent magnetization due to compression p is given by

$$dJ_r = -4 \cdot \pi \cdot N \cdot a \cdot d\{f(p) \cdot J_r\} \quad (5-1)$$

Integrating (5-1), we obtain the resultant remanent magnetization after compression in a non-magnetic space as

$$(J_r)_p^{H_{ex}=0} \equiv J_r(H+, HO, P+, PO) = \frac{C \cdot J_r}{1 + 4\pi \cdot N \cdot a \cdot f(p)} \quad (5-2)$$

where C , a and $f(p)$ are undetermined constant of integration, a constant of proportionality and a hyperbolic function of p given in eq. (3-1). The value of $(J_r)_p^{H_{ex}=0}$ can be calculated numerically using values of $f(p)$ obtained from the PRM versus pressure relations in Figs. 4 and 5. The tendency of pressure demagnetization by uniaxial compression in Figs. 13 and 14 is well explained by eq. (5-2).

5-2 Piezo-effect of PRM

Fig. 15-a PRM induced in two directions perpendicular to each other.

1) Pressure axis is parallel to the direction of magnetic field of 30 Oe ($J_{pr}^{\parallel}$).

2) The former is perpendicular to the latter ($J_{pr}^{\perp}$).

Sample is an assemblage of fine grains of titanomagnetite with a grain size of less than 70 microns packed in a cylindrical shape of 10 mm in diameter and 10 mm in length.

Fig. 15-b Deviation $\Delta\theta$ of the PRM vector (J_{pr}) from the external magnetic field (H), calculated as a function of θ , from the curves in Fig. 15-a.

The dependence of PRM intensity upon pressure p was examined in two cases; 1) where the axis of compressional stress is parallel to the direction of an external magnetic field, and 2) where the former is perpendicular to the latter. In both cases, the direction of PRM is parallel to that of the external magnetic field.

Although the demagnetizing factors of the specimens are chosen to be nearly equal in both directions, the intensity of PRM in the case of “pressure perpendicular to magnetic field” (denoted as $J_{pr}^{\perp}$) is systematically larger than that of “pressure parallel to magnetic field” ($J_{pr}^{\parallel}$) as shown in Fig. 15-a. In the Rayleigh region of an external magnetic field (less than 100 Oe), $J_{pr}^{\perp}$ and $J_{pr}^{\parallel}$ are expressed by

$$J_{pr}^{\perp} = a \cdot H_{ex} \cdot f(p) \cdot (1+k) \quad \text{and} \quad J_{pr}^{\parallel} = a \cdot H_{ex} \cdot f(p) \quad (5-3)$$

where k is a positive constant. Above 1 kb, the constant k is approximately equal to 0.4. Therefore, if H_{ex} makes an angle θ with the pressure axis, the resultant PRM becomes, from eqs. (5-3)

$$J_{pr}^{\perp} = a \cdot H_{ex} \cdot f(p) \cdot (1+k) \sin \theta \quad \text{and} \quad J_{pr}^{\parallel} = a \cdot H_{ex} \cdot f(p) \cdot \cos \theta \quad (5-4)$$

Putting $\tan \alpha = J_{pr}^{\perp} / J_{pr}^{\parallel}$ and $\Delta\theta = \alpha - \theta$, $\Delta\theta$ becomes

$$\Delta\theta = \tan^{-1} \{ k \cdot \sin^2 \theta / (1 + k \sin^2 \theta) \} \quad (5-5)$$

The numerical value of eq. (5-5) is plotted in Fig. 15-b as a function of θ . Obviously $\Delta\theta$ is positive, i.e., J_{pr} will be deflected from the direction of the external magnetic field toward the plane perpendicular to the axis of uniaxial compression. An apparent similar phenomenon of piezo-magnetism in natural rocks has been observed as NRM by Domen (1962).

6. Concluding remarks

PRM reported in this paper can consistently be explained through an inverse effect of the

magnetostriction. According to the theory of magneto-elasticity, an external axial stress inevitably induces a magnetic anisotropy which rotates the spontaneous magnetization of individual magnetic domains. Its equilibrium condition is given by a balance between the energies of the stress-induced anisotropy and magnetocrystalline anisotropy, the latter which acts as restoring force against the rotation of magnetic spins. When both magneto-static energy induced by an external magnetic field and magnetocrystalline anisotropy energy are overcome by the stress-induced anisotropy energy, the direction of individual spontaneous magnetizations will be dependent solely on the external mechanical force. If the specimen is completely demagnetized in an initial stage, i.e., when the spontaneous magnetization is homogeneously distributed, an external stress must easily induce an irreversible change in the direction of the magnetization of each domain, even in a weak external magnetic field. A more detailed quantitative explanation of this problem will be given in a future paper.

The author is very grateful to Prof. T. Nagata for his helpful discussions.

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