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STRESS-INDUCED MAGNETIZATION IN SMALL MAGNETIC FIELDS

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Résumé. — On étudie les variations d’aimantation dues à l’application simultanée de champs magnétiques et de contraintes (tractions et compressions) sur certains matériaux ferromagnétiques comprenant quelques alliages de fer-carbon qui ont subi divers traitements métallurgiques. Lorsqu’un petit champ suivi par une contrainte sont appliqués sur un échantillon (HP) la courbe d’aimantation en fonction de la contrainte qui en résulte n’est pas symétrique (en contrainte) pour presque tous les matériaux considérés. Même pour des champs et contraintes très faibles, la pente de la courbe d’aimantation-contrainte est supérieure lorsque la contrainte (α) a le même signe que le coefficient de magnétostriction que lorsque la contrainte a le signe opposé (par exemple, dans le cas du fer, où α est positif, la pente de la courbe d’aimantation-contrainte est beaucoup plus grande pour une tension que pour une compression). Un comportement irrégulier est aussi observé pour le processus HPP qui dénote l’application d’un champ suivi de l’application d’une contrainte puis de sa suppression.

Abstract. — The variation of magnetization produced by the simultaneous application of magnetic fields and stresses (both tensile and compressive) has been studied for a number of ferromagnetic materials including iron-carbon alloys that have been subjected to various metallurgical treatments. When a small magnetic field and then a stress is applied to a specimen (HP), the resulting magnetization-stress curve is unsymmetrical (in stress) for almost all the materials considered. Even for very weak fields and stresses, the slope of the magnetization-stress curve is greater when the stress (α) has the same sign as the magnetostriction coefficient (λ) than it is when the stress has the opposite sign (e. g. in the case of iron, where λ is positive, the slope of the magnetization-stress curve is much larger for tension than for compression). Anomalous behaviour is also observed in the process HP, which denotes the application of a field followed by the application of a stress and then its subsequent removal.

1. Introduction. — Existing theories [1, 2] of stress-induced changes in magnetization in small fields, whilst in good agreement with experimental data [3, 4] previously available, make two predictions that are not borne out by the results of the present investigation, reported below. Specifically, these theories predict that the stress-induced magnetization will, first, be even in the stress and will, secondly, increase monotonically with stress. In practice, as indicated below, the initial slopes of the curves of magnetization versus stress are generally unequal for tension and for compression, whilst for large compressive stresses anomalous behaviour is observed involving the appearance of maxima in the experimental curves.

2. Experiment. — A comprehensive investigation has been made of the magnetization changes that accompany the simultaneous application of field and (tensile and compressive) stress for a number of ferromagnetic materials including some Ni-Fe alloys and a series of iron-carbon alloys (ranging from spectrographically pure iron to a steel containing 0.20 wt. % carbon).

For the Fe-C alloys it is found that specimens with low values of internal stress (annealed, low carbon-content materials) display the largest inequalities in initial slopes, whilst specimens with large values of internal stress (swaged, high carbon-content materials) exhibit only very small inequalities. In fact, figures 1 and 2 are typical, respectively, of the behaviour observed for opposite ends of a series obtained by arranging the specimens — on a metallurgical basis — in order of increasing magnitude of residual internal stress.

The anomalous behaviour (for the process HP) involving the appearance of a maximum for compression is clearly shown in figure 1. Since existing theories [1, 2] predict a horizontal « fly-back » on removal of the stress — somewhat as shown in figure 2 — anomalous behaviour is also evident for the process HPP. This may be most clearly seen from the intermediate fly-back (from 2 kg.mm$^{-2}$) in figure 2, which indicates that there is a marked increase in magnetization with decreasing stress.

The measurements on the Ni-Fe alloys showed that for the composition range in which the magneto-
Fig. 2. — Stress-induced magnetization at 1 Oe for an Fe-0.20 wt % C alloy with a 75 % reduction in cross-sectional area.

3. Discussion. — The anomalous behaviour at large compressive stresses, in which the magnetization attains a maximum and then decreases with further compression, can be anticipated from previous domain observations on Co-Fe-C alloys. It is to be expected that the effect of tension and compression applied along a [001] direction are quite different, in that for tension the primary domains remain parallel to this direction, whilst for compression a discontinuous change takes place to a completely new domain pattern in which the primary domain magnetization is perpendicular to the [001] direction. It is to be expected that this characteristic behaviour will also be found for polycrystals, with the [001] direction then being replaced by the easy direction most nearly parallel to the axis of stress in each crystalline grain. Hence, if the magnetization is measured parallel to the stress axis, the application of large stresses will be accompanied by an increase in magnetization for tension but by an (eventual) reduction in magnetization for compression.

The inherent asymmetry of the discontinuous changes with respect to positive and negative stress should, of course, also be observed at smaller stresses. Corner and Mason give 0.02 kg.mm² as a critical stress for the onset of such changes and therefore the magnetization attained in tension is expected to be greater than that in compression even for such small stresses. However, there is, as indicated below, another factor partly responsible for the marked inequality of slopes observed experimentally for annealed materials.

Initially, in the absence of a stress, there will be, within each polycrystalline grain, a preferential occupancy by domain magnetization of the two easy directions lying most nearly parallel and antiparallel to the field direction and the volume of the parallel domains will clearly exceed that of the antiparallel domains. Moreover, although these two sets of primary domains are separated by 180° walls they will nevertheless have associated with them closure domain structures involving 90° walls. Both sets of primary domains will therefore be divided from perpendicularly magnetized closure domains by 90° walls but the parallel domains (having the larger volume) will have associated with them (i.e. bounding them) a larger total area of these walls than will the antiparallel domains (having the smaller volume). Since the stress axis is close to the directions of the domain magnetizations in the primary domains, the application of a tensile stress tends to promote the growth of primary domains at the expense of closure domains. This means that the 90° domain walls of larger total area (bounding the parallel primary domains) move in the same sense as for an increase in the applied field, whereas the 90° walls of smaller total area (bounding the antiparallel domains) move in the opposite sense. Conversely, the application of a compressive stress tends to promote the growth of closure domains at the expense of the primary domains, which means that now the 90° walls of larger total area (bounding the parallel primary domains) move in a sense contrary to that produced by an increase in the applied field, whereas the 90° walls of smaller total area (bounding the antiparallel domains) move in the same sense. Hence, in the polycrystalline case also, for tension the 90° walls of larger total area are of type (i) but for compression they are of type (ii), where (i) labels walls for which field and stress tend to produce wall motion in the same sense and (ii) labels walls for which they tend to produce motion in the opposite sense.

In a theoretical treatment, the magnetization changes corresponding to the movements of walls of type (i) and type (ii) must be added together algebraically after multiplication by a weighting factor proportional to their respective areas. It therefore follows immediately that the effect of changing from a ratio of areas of walls of type (i) to type (ii) that is greater than unity for tension to one that is less than unity for compression is to increase the initial slope of the curve of magnetization versus tension over the initial slope of the curve of magnetization versus compression. Moreover, this inequality of initial slopes will clearly increase with an increase in the initial magnetic field used, since the field is exactly the factor that is responsible for the ratio being different from unity in the first place. Furthermore, a change from positive to negative magnetostriction merely interchanges the roles of walls of type (i) and (ii), so that the effect upon the initial slope ratio of changing the sign of the magnetostriction should be precisely that which is observed experimentally. It is also clear, from what has been said above, that an experimental value of either initial slope (or curvature) must first be averaged between tension and compression before any comparison with theory is attempted.

It now remains only to comment further on the differences observed experimentally between the soft and the hard Fe-C alloys. The marked inequality in initial slopes for annealed materials is obviously in conformity with what has been said above, whereas, for materials with large values of internal stress, only a very small slope inequality is to be expected because the initial field will produce only small move-
ments of domain walls so that not only is the onset of discontinuous changes deferred but also the total area of type (i) walls will remain very nearly equal to that of type (ii) walls. The behaviour of these alloys can also be compared with theory by considering how the ratio of the (averaged) initial slope to curvature (theoretically about $32 H/7 \pi$) depends upon hardness. Existing theories [1, 2] assume (correctly) that the application of a stress alters the pressure on a domain wall but do not, explicitly, envisage any alteration in the opposition term, which must clearly be in balance with this pressure for domain wall equilibrium. This assumption is likely to be realistic for soft, annealed materials but, as the magnitude of the internal stress is increased, it is to be expected that the effect of stress-induced changes in the opposition term will become more important and, consequently, theoretical predictions based only on an alteration in the pressure on a domain wall will become less appropriate. However, a complication exists because stresses of practical importance can already be larger than that which may be needed to produce discontinuous changes in domain structure as mentioned previously, for the latter, Corner and Mason quote a figure as low as 0.02 kg.mm². Usually, therefore, experimental data would yield apparent ratios of initial slope to curvature different from the true ratios appropriate to the limit as $\sigma$ tends to zero. Nevertheless, it may be expected that the departure of the true ratio from the theoretical value (about $32 H/7 \pi$) will be reflected in a corresponding departure for the apparent ratio. For low fields (i.e. within the Rayleigh region) the experimental data confirm these ideas in that the apparent ratios are, in general, of the order of $32 H/7 \pi$ for the soft materials but are a few times larger for the harder materials. This observation can, of course, be readily explained if the stress-induced changes in the opposition term mentioned above are approximately linear in $\sigma$.

A more detailed account of the experimental results discussed above will be presented elsewhere.

References