MAGNETIZATION REVERSAL IN AMORPHOUS $(Fe_{1-x}Ni_x)_{80}P_{10}B_{10}$ MICROWIRES

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The low-field magnetic properties of amorphous $(Fe_{1-x}Ni_x)_{80}P_{10}B_{10}$ are examined by measuring the local magnetic reversal field and the pinning field as function of position. Also measurements of magnetic anisotropy using FMR are reported. The observed magnetic behaviour is discussed generally. The magnetization reversal for the ideal parts of the wires may be described by the process of growth of nuclei present.

1. INTRODUCTION

The intrinsic magnetic properties of amorphous metallic glasses have been investigated extensively during recent years. With new advances in material synthesis continuous ribbons and wires have been prepared in a form suitable also for low-field measurements. The present data indicate that remarkably soft magnetic properties can be obtained for some of the transition-metal based alloys [1, 2].

Much work on magnetic reversal behaviour has been done on amorphous ribbons. In general the coercive field of a ferromagnetic material is determined either by domain wall pinning or by nucleation. Domain observations [1] as well as studies of the dependence of coercive force on concentration [1, 3] and on temperature [4] indicate that the pinning mechanisms are important for such materials. But BECKER [5] reported also nucleation dominated reversal in amorphous Fe – Ni based ribbons. According to the paper by O'HANDLEY [6] the magnetization reversal in amorphous wires is dominated by nucleation.

In this paper we report measurements of the magnetic anisotropy of amorphous $(Fe_{1-x}Ni_x)_{80}P_{10}B_{10}$ microwires using FMR and discuss the observed magnetic reversal behaviour. Our measurements indicate that in these amorphous wires the hysteresis is not controlled by nucleation in spite of rectangular loops.

2. EXPERIMENTAL PROCEDURE

Amorphous $(Fe_{1-x}Ni_x)_{80}P_{10}B_{10}$ alloys with $x = 0$; 0·1; ...; 0·6 were prepared by the Taylor technique described previously [7]. The as-prepared microwires of diameters from 5 to 25 μm have an ideal cylindrical form and are covered by

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a few μm thick glass coat. All the samples used were examined by X-ray diffraction. They were considered to be amorphous since the diffraction patterns showed only one diffuse ring.

Magnetic properties were studied on both as-prepared wires and wires without the glass coat. The glass coat was removed by etching in HF acid. FMR measurements were done on about 1·5 mm long pieces of such wires. The dc magnetic field

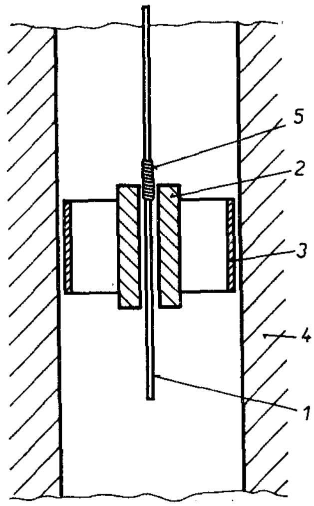

Fig. 1. Arrangement for low-field magnetic measurements, 1 — capillary with the sample, 2 — pick up coil, 3 — compensation coil, 4 — magnetizing solenoid, 5 — nucleation coil.

was applied parallel to the axis of the wire. The microwave frequencies used were in the range from 9·2 to 36·2 GHz. From measurements at three different frequencies the saturation magnetization M_s, the spectroscopic splitting factor g, and the effective anisotropy field were determined. The low-field magnetic properties were studied on 5 to 7 cm long pieces of wires. An induction method with a recording fluxmeter was used for the M vs. H loop measurements at room temperature with fields up to 300 Oe (see Fig. 1). Technical saturation was reached in all cases in much lower fields. For the local magnetization reversal field and domain wall pinning field measurements a small nucleation coil was used.

3. RESULTS AND DISCUSSION

The low- and high-field hysteresis loops of all wires in the as-prepared form are ideally rectangular (see Fig. 2a). After removing the glass coat, rounded high field hysteresis loops are observed whereas the low-field loops do not change their more or less rectangular character (Fig. 2b). The coercive force H_c decreases (in some cases down to 1/4 of the value in the as-prepared samples), and the remanence-to-saturation ratio M_r/M_s decreases from unity to about 0·6–0·9. The technique for producing thin wires, used by us, can be described as a quenching process under tensile stress. So we expect besides the inevitable inhomogeneous internal stress-induced anisotropy a uniform macroscopic magnetic anisotropy of magnetostrictive origin.

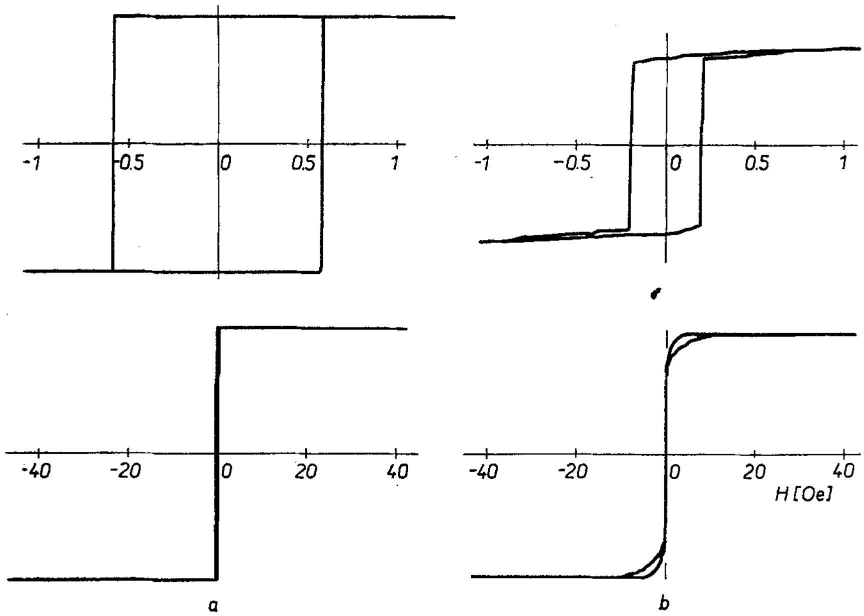

Fig. 2. Hysteresis loops of amorphous $Fe_{80}P_{10}B_{10}$: a) as-prepared microwire and b) microwire without the glass coat.

Values of the magnetic anisotropy fields determined by FMR are compiled in Table I. The anisotropy field of as-prepared wires H_k scatter even for different samples of the same alloy, as can be seen in Table Ia. There is also no correlation between the values of H_k and the chemical composition. The effect of the glass coat on H_k is well demonstrated by the values of ΔH_k (Table Ib). From the measurements it may be concluded that the as-prepared microwires exhibit a uniaxial macroscopic magnetic anisotropy with the easy axis parallel to the axis of the wire, which is caused mainly by the stress due to the glass coat. The anisotropy constant $K_{\parallel} = \frac{1}{2}M_sH_k$ is of the order of $1 \div 20 \times 10^4$ erg/cm^3. Using the previous measured values of λ_s [8] and the values of ΔH_k one finds for the stress induced by the glass coat values of 0·5 to 47 kp/mm^2 (4·9 to 460 MPa).

Ferromagnetic resonance linewidth investigations show that even the best samples exhibit an inhomogeneous broadening of the resonance line of several Oe. A local random uniaxial magnetic anistrotropy of the order of $K_{eff} \sim 5 \times 10^2$ erg/cm^3 may be a source of this broadening. Anisotropy constants of the wires without the glass coat determined from the area above the hysteresis loops are of the same order.

Table I

	a)	b)		
x	H_k [Oe]	H_k	H_{k_1}	ΔH_k [Oe]
0	70, 73, 51	70	46	24
0·1	167, 401	401	45	356
0·2	198, 102	198	21	177
0·3	227, 212, 247	212	24	188
0·4	259, 30, 28	259	20	239
0·5	89, 66, 107	89	3	86
0·6	72, 218, 109	218	5	213

a) Anisotropy fields H_k of amorphous $(Fe_{1-x}Ni_x)_{80}P_{10}B_{10}$ microwires from FMR measured on as-prepared samples (with the glass coat).

b) Anisotropy fields H_k resp. H_{k_1} of the same sample with resp. without the glass coat. $\Delta H_k = H_k - H_{k_1}$ is the stress anisotropy field due to the glass coat.

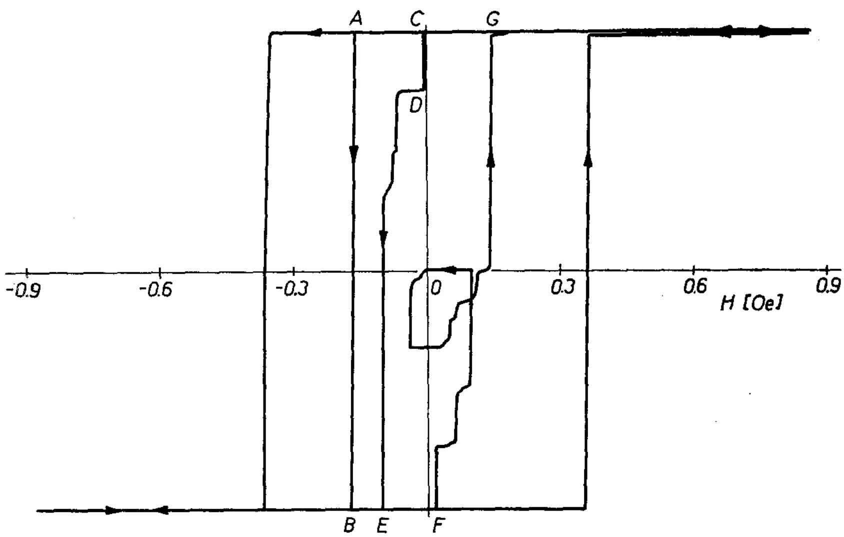

Fig. 3. Magnetization curves of amorphous as-prepared $Fe_{80}P_{10}B_{10}$ wire. A, B, C, D, E see text. F—G the minor hysteresis loop due to domain wall movement.

In order to eliminate the end effects in the discussion of the magnetic reversal behaviour we measured the local magnetic reversal field H_l as well as the pinning field H_p as function of position. Applying a magnetic field locally by means of the nucleation coil (Fig. 1) the magnetization reversal may be evoked at a homogeneous background field smaller than the coercive force, as shown by line A—B in Fig. 3.

The sum of the background field and field of the nucleation coil determines the local reversal field H_l. (We use here the term "local reversal field" instead of nucleation field because it need not be nucleation which determines the local magnetization reversal behaviour.) If the homogeneous background field is smaller than the maximum critical field for domain wall movement, the domain walls of the locally created domain are caught by some imperfections and magnetization can be reversed only in a part of the wire (point D). Increasing the background field above the pinning field H_p the domain wall becomes free and moves to the next pinning centre with higher H_p. In this case the magnetization curve shows a few Barkhausen jumps (curve C−D−E).

The smallest value of H_l is found in each case at the end of the wire (see Fig. 4a). This value gives also H_c of the measured M vs. H loops. The pinning fields H_p are smaller than minimum H_l, as can be seen from Fig. 4b. This explains the fact that the hysteresis loops approach the ideally rectangular shape. In a few cases we found some local H_p which exceeded the minimum of H_l. In this case the hysteresis loop shows two or more discontinuous jumps. At first sight the magnetization reversal dominated by nucleation seems to explain all the above described low-field magnetic properties. But as can be seen later, the values of H_l do not agree with the nucleation theory.

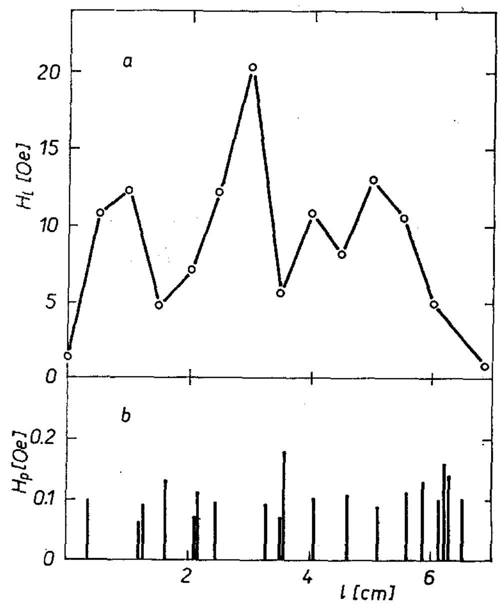

Fig. 4. Local magnetization reversal field H_l and pinning field H_p of as-prepared $(Fe_{0.5}Ni_{0.5})_{80}P_{10}B_{10}$ as function of position.

After removing the glass coat a decrease of H_l was observed. The reduction of H_l becomes larger (down to 7% of the initial value) for samples with strong anistropy fields in the as-prepared state. On the other hand, H_p is nearly the same for the wires with and without the glass coat. This indicates that the local reversal field H_l is strongly influenced by the stress induced uniaxial anisotropy but the pinning centres are of other than magnetostrictive origin. The dependence of $\overline{H}_l$ (average of H_l over the central portion of the wires eliminating the end effects) as a function of $\overline{H}_k$ is shown in Fig. 5 for as-prepared samples. $\overline{H}_k$ gives the averaged value of the anisotropy fields measured by FMR for different samples of the same composition. The tendency of $\overline{H}_l$ to increase with increasing $\overline{H}_k$ can be seen in this figure. However, the values of $\overline{H}_l$ are much smaller than the nucleation field of the curling mode, i.e. $H_l = H_k$ (dashed line in Fig. 5).

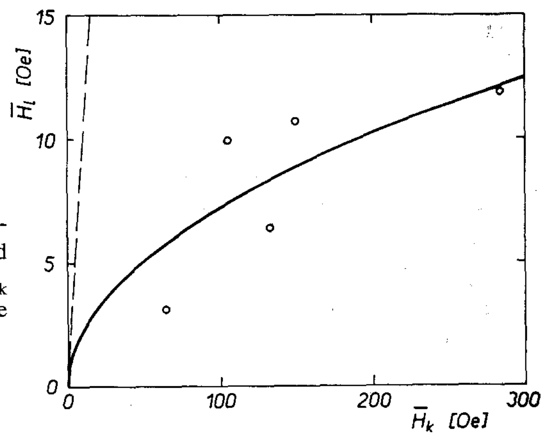

Fig. 5. $\overline{H}_l$ as function of $\overline{H}_k$ of as-prepared microwires ($\overline{H}_l$, $\overline{H}_k$ — averaged values). The dashed line gives $H_l = H_k$ for the curling mode. The full line represents $H_l \sim H_k^{1/2}$.

According to the works by HAAKE, DÖRING and others on permalloy wires (summarized e.g. in [10]), nuclei play an important role in the magnetization reversal process. The growth of such a nucleus is qualitatively different from the growth of a domain which would extend over the whole cross-section of the wire. In contrast to the latter case the former one cannot grow without increasing its domain wall area (surface energy). DÖRING used a model of a prolate spheroidal nucleus in an infinite ferromagnetic medium. That model cannot describe the real situation in wires especially when the nuclei are formed at the surface [15]. But no realistic model which would take into account the surface effects and imperfections of the material has been developed yet. Nevertheless as far as the surface energy of the nucleus dominates DÖRING's theory gives the local reversal field (the *starting field* according to Döring's notation) proportional to the domain wall energy density which varies as $H_k^{1/2}$. We believe this result to be generally valid even though Döring's model is probably not quite adequate to the real situation. Despite the large statistical error, our results are in better accordance with the $H_k^{1/2}$ dependence (full line in Fig. 5) than with the nucleation theory. The proportionality of H_l on $H_k^{1/2}$ was fully confirmed by measurements under applied stress [9]. So we conclude that not nucleation but the critical field for the growth of already present nuclei dominates the magnetization reversal behaviour.

The nuclei of subcritical dimensions are beyond the sensitivity limits of our apparatus and their continuous growth cannot be observed on magnetization curves. The presence of the nuclei is, however, also indicated by other slightly more involved pulse experiments (similar to those reported by HAAKE [11]) which we have performed on our wires.

4. CONCLUSION

The magnetic reversal behaviour of these Fe–Ni based alloys may be well understood on the assumption of a uniaxial macroscopic magnetic anisotropy superimposed upon a smaller random local magnetic anisotropy.

The magnetization reversal process of the whole as-prepared wire is controlled by the local reversal at the ends. The pinning fields are lower than the local magnetic reversal fields, which results in ideally rectangular hysteresis loops. The glass coat acts like an external stress. The same mechanism applies for the amorphous wires without the glass coat. The high field loops become rounded, which may be attributed to some residual domains or to a noncomplete alignment of the spatial magnetization (ripple structure). This may be caused by the local random magnetic anisotropy, which becomes much more effective, if the large macroscopic uniaxial magnetic anisotropy is significantly reduced. The value of the effective random anisotropy constant K_{eff} estimated from the area above the high-field magnetization curve is of the order of 5×10^2 erg/cm^3. This is in excellent agreement with the value determined from the linewidth of the FMR curve.

The magnetic reversal behaviour of these amorphous transition-metal based wires is quite different from that observed for iron whiskers [12, 13] and thin nickel fibers [14] in which the domain-nucleation field determines the reversal process. This fact proves the existence of nuclei in amorphous wires which either never disappear or are spontaneously formed at a magnetic field lower than the local reversal field H_l. Therefore, H_l is smaller in amorphous materials than in perfect crystalline ones. This may be caused by a larger amount of defects (fluctuations of all kinds) on a fine spatial scale in such amorphous metallic glasses.

The authors wish to thank Dr. J. KACZÉR and Dr. I. TOMÁŠ for helpful discussions as well as comments on the manuscript.

Received 29. 11. 1977.

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