Continuous Magnetization Patterns in Amorphous Ribbons

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***Abstract*—Continuously rotating magnetization configurations rather than regular magnetic domains are observed by Kerr microscopy in magnetostriction-free amorphous ribbons after heat treatment in a rotating magnetic field. An almost anisotropy-free state is thus generated in which domain walls are no longer defined. Continuous patterns are also found close to the surface of ribbons with perpendicular or oblique anisotropy, where regular closure domains cannot exist because of conflicting influences of anisotropy and pole avoidance.**

***Index Terms*—Amorphous materials, Kerr microscopy, magnetic domains, magnetic microstructure, soft magnetic materials.**

I. Introduction

CONTINUOUSLY rotating magnetization configurations (on a scale larger than the domain walls) are well known to occur in soft magnetic thin film elements with rounded edges (like ellipses or disks) where they are a natural extension of van-den-Bergs domain concept [1]. Continuous structures are theoretically expected to exist also in bulk materials in the case of a vanishing anisotropy. As the width of a domain wall in thick materials scales with $\sqrt{(A/K)}$, where A is the exchange constant and K is an anisotropy constant, the walls should become infinitely extended for zero anisotropy so that the distinction between domains and walls would become meaningless. Continuously flowing, divergence-free patterns, perhaps comparable to the velocity field in hydrodynamics, should then replace regular domains.

Nevertheless, based on domain observations on a variety of materials in [2] we came to the conclusion that such continuous patterns are not observed in a real bulk magnet because anisotropy seems never to be small enough. This is even true for extremely soft magnetic materials [3] like amorphous metals where crystal anisotropy is zero by definition. Here residual anisotropies, caused by internal stress or induced by the magnetization present during quenching, are responsible for more or less regular domain patterns with identifiable walls in all domain images presented hitherto.

Recently, however, we were able to prepare amorphous material with strongly reduced residual anisotropy. This was possible by annealing magnetostriction-free ribbons in a rotating magnetic field. The magnetic microstructure of such ribbons is presented here by digitally enhanced Kerr-microscopy. We also show that continuous configurations can occur in surface zones of amorphous ribbons with well-defined anisotropy, if regular domains cannot exist because of conflicting influences of anisotropy and pole avoidance. A two-dimensional oscillation of the surface magnetization is already known from ribbons with an anisotropy perpendicular to the ribbon surface [4], [10]. Here we present the first observation of a one-dimensional oscillation for ribbons with an obliquely oriented easy axis.

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II. Results and Discussion

A. Anisotropy-Free Ribbons

To obtain a largely anisotropy-free amorphous material, a commercial ribbon of the nominally magnetostriction-free alloy $Co_{68}Fe_4Mo_2Si_{16}B_{10}$ (VITROVAC6025 from Vacuumschmelze, $\lambda_s = -0.1 \times 10^{-6}$) was chosen. Due to its high crystallization temperature of 540 °C it offers the potential of an effective stress relief by annealing, while at the same time the Curie temperature is as low as 220 °C so that magnetization-induced anisotropy, created during cooling after passing the Curie point, can be kept small (<0.5 J/m^3). Disks with a diameter of six millimeters were cut by spark erosion and carefully polished on both sides to reduce anisotropy effects from the surfaces. The disks with a final thickness of 17 μm were annealed in vacuum at 430 °C for one hour, and cooled to room temperature in the presence of a magnetic field of some 100 A/cm that was rotating in the ribbon plane at 50 Hz.

The effect of this treatment on the magnetic microstructure is shown in Fig. 1. The arrows in the pictures were measured by evaluating the Kerr contrast in a quantitative procedure [5]. If a domain wall in the as-quenched state [Fig. 1(a)] still has a finite width of about 1 μm, caused by residual anisotropy, a wall width can hardly be assigned after annealing in the rotating field [Fig. 1(b)]. Domain walls may even become completely dissolved [Fig. 1(c)] and a magnetic microstructures is observed that may in fact be called "continuously flowing." It is characterized by ill-defined domain walls and by the presence of vortices which are unavoidable for topological reasons [6], [2]. Some further examples of such patterns are collected in Fig. 2. The vortices are actually magnetization swirls—quasisingularities in which the magnetization turns perpendicular to the surface toward the vortex core (thus avoiding a true singularity—see [2]).

The importance of the rotating field is demonstrated in Fig. 3. If a ribbon of the same composition is stress-relief annealed and cooled in the absence of a magnetic field, domain wall pinning [7] is observed. This shows that a nonnegligible anisotropy is induced in the absence of a rotating magnetic field during annealing, even if it is supposed to be below one J/m^3.

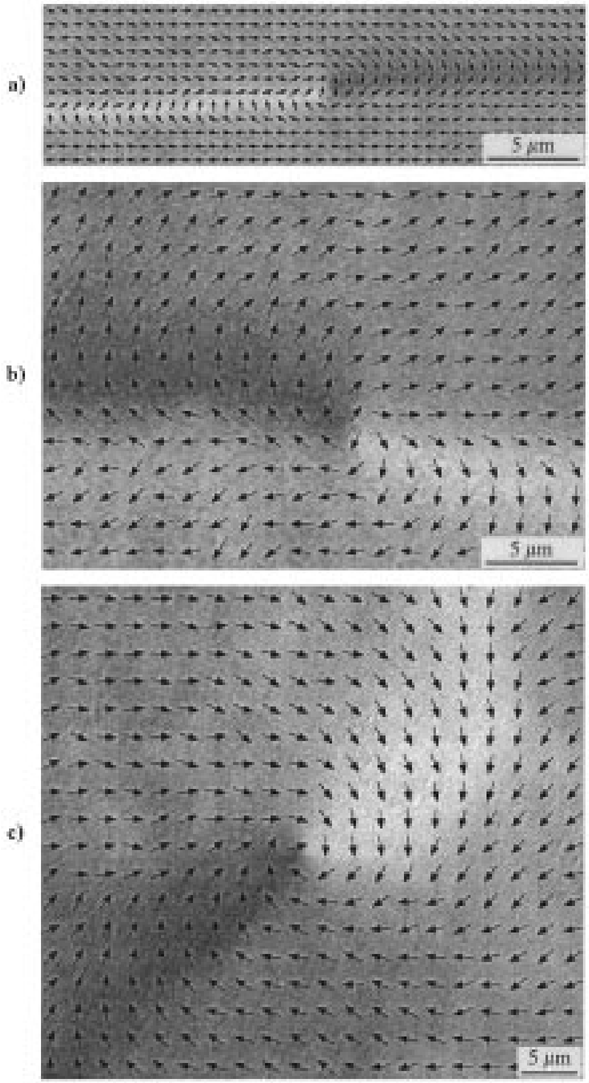

Fig. 1. (a) 180° domain wall in a magnetostriction-free amorphous ribbon in the as-quenched state. (b), (c) Continuously flowing configurations in the same material after stress-relief annealing and cooling in a rotating magnetic field. The arrows were determined by quantitative Kerr microscopy.

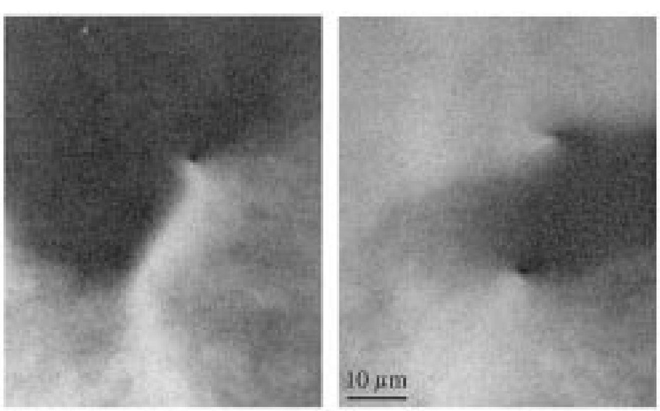

Fig. 2. Continuous magnetization patterns [same sample as in Fig. 1(b), (c)].

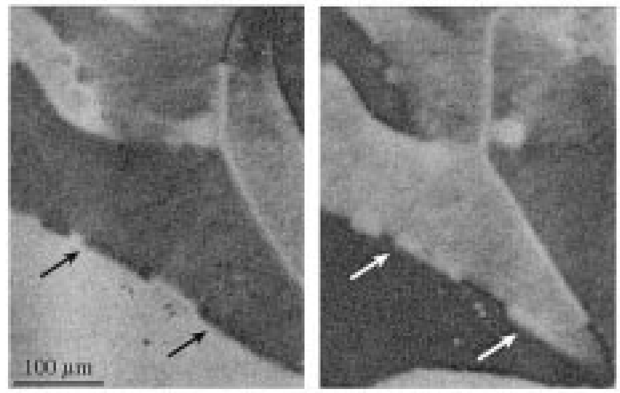

Fig. 3. Pinned domain wall (marked by arrows) in a ribbon that was cooled in the absence of an external field after stress relief annealing. The sample was independently demagnetized for both images. The position of the pinned wall is evident from the domain changes in the neighborhood.

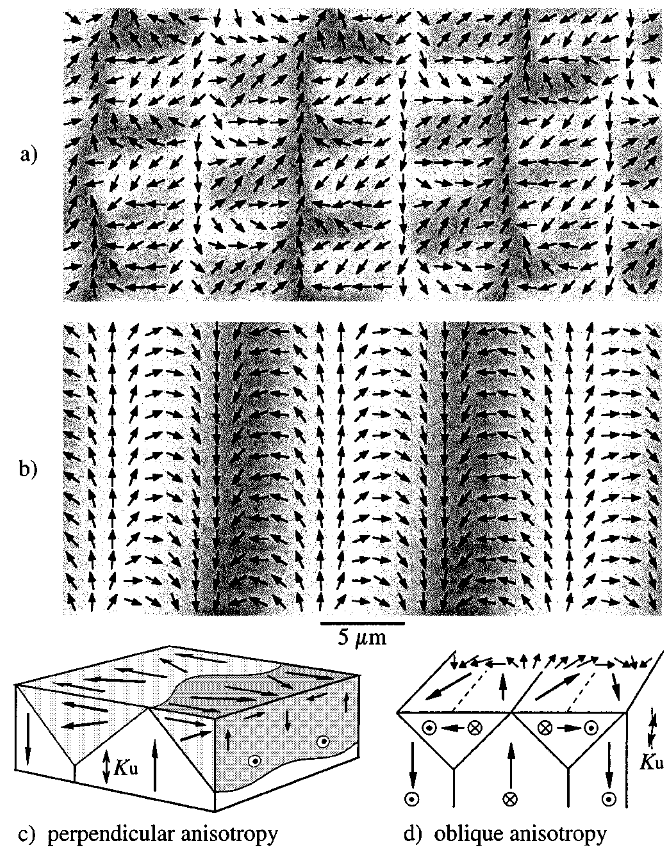

Fig. 4. Quantitatively evaluated magnetization patterns at the surface of magnetostrictive amorphous ribbons, in which a uniaxial anisotropy was induced by field annealing. A two-dimensional surface oscillation is observed in the case of perpendicular anisotropy (a), whereas for oblique anisotropy a one-dimensional oscillation is found (b). In (b) the ribbon was demagnetized in a magnetic field along the (horizontal) ribbon axis before observation, and the easy axis is tilted by some degrees away from the perpendicular axis toward the transverse direction. Schematic models for the two cases are shown in (c) [4], [10] and (d) [9].

B. Anisotropic Ribbons

In the foregoing examples we could prove that the magnetic microstructure of amorphous ribbons is continuously flowing if residual anisotropies are sufficiently reduced. Paradoxically, there are situations in which continuous structures may even require the presence of anisotropy. In [4], [10] this was demonstrated for ribbons with a stress-induced perpendicular anisotropy: The closure domains of internal perpendicular domains are under the conflicting influences of anisotropy (which favors the perpendicular direction) and pole avoidance (which favors an in-plane closure domain magnetization). The answer to this conflict is a continuous and periodic modulation of magnetization in a three-dimensional way close to the ribbon surface, which may proceed in several generations of submodulations for increasing anisotropy [2].

Fig. 4(a) shows such a configuration that is two-dimensionally modulated right at the surface. In this case, however, the perpendicular anisotropy is not stress-induced. It was rather generated by annealing a $Fe_{24}Co_{18}Ni_{40}Si_2B_{16}$-amorphous ribbon in a perpendicular magnetic field of 1 Tesla (annealing temperature 350 °C, annealing time 6 sec). A one-dimensional surface modulation [Fig. 4(b)] develops if the symmetry is broken by slightly tilting the easy axis out of the perpendicular direction. This can either be obtained by annealing in a tilted field or in a perpendicular field that is insufficient to completely force the magnetization along the perpendicular direction due to demagnetization effects [8]. Domain observation thus offers a unique possibility to decide whether the anisotropy axis is aligned obliquely (one-dimensional surface oscillation) or perpendicularly (two-dimensional oscillation). This would not easily be possible by integrating magnetization measurements.

III. Summary

Annealing magnetostriction-free amorphous ribbons in a rotating magnetic field allows the reduction of residual anisotropies to such a degree, that regular magnetic domains are replaced by continuously flowing magnetization patterns. Continuous, but periodic configurations also play a role for flux closure at the surfaces of ribbons with a strong out-of plane anisotropy.

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