Small-angle neutron studies have been performed on samples of continuous inhomogeneous magnetic recording media. This has allowed the local magnetic structure to be probed at a sub-nanometre resolution, revealing some interesting information about the size and shape of the magnetic grains and their relation to the physical grains.

INTRODUCTION

There have been relatively few neutron studies of the local magnetic structure of continuous magnetic recording media [1,2]. This paucity is in part due to the difficulties of performing scattering experiments on the tiny volumes of magnetic material available in real systems. Experiments have therefore sometimes focused on thick films of related alloys, that lack the dimensions, underlayers and processing history that give thin film recording media their very particular structure and properties.

We have performed a number of studies on longitudinal thin film media intended for use in hard disk drives. These experiments are extremely challenging to perform, due to the small magnetic volume of the active layer (ca. 20 nm) and the large amount of background scattering from the substrate and underlayers. Nonetheless, for those systems where the distribution of grain sizes is relatively narrow, a surprising amount of information can be extracted concerning the local magnetic structure. In this paper we focus on results from one particular material, a CoCrPtB alloy with a grain diameter of around 11 nm.

EXPERIMENTAL DETAILS

The samples were sputtered onto Al substrates, beginning with a thick layer of NiP (ca. 1000 nm), followed by a series of non-magnetic seed layers of typical thickness of 10-20 nm, and finally the CoCrPtB layer of thickness 20 nm, this layer being capped with 7 nm of carbon. Due to the large amount of metallurgical scattering from microscopic structure at small angles, much of the Al substrate was removed by careful abrasion to reduce this contribution. In order to increase the volume of magnetic material available for scattering, the sample comprised around thirty polished coupons of diameter 18 mm.

The small-angle neutron (SANS) experiments were carried out using the D11 spectrometer at the ILL, Grenoble. The neutrons have both a nuclear and a magnetic scattering cross-section that are roughly comparable in magnitude. However, due to the tiny magnetic volume of these samples, the
scattering from the structural disorder dominates the raw scattering data, to the extent that the magnetic signal cannot be extracted simply. However, unlike the nuclear cross-section, which is isotropic, the magnetic signal varies as $I_M \propto \sin^2 \theta$, where $\theta$ is the angle between the scattering vector and the local direction of the magnetisation. This anisotropy may thus be used to reveal the magnetic scattering in the following way. Firstly a sample is prepared for which the local magnetisation is randomised over $2\pi$ (in the plane of the film). The neutrons are incident normal to the plane of the film and are scattering through small angles to give an isotropic pattern containing both a magnetic and a much larger nuclear contribution. A field is then applied to saturate the magnetisation in the plane of the film, which gives rise to an anisotropic magnetic scattering. This can be revealed by subtraction of the zero-field isotropic pattern to remove the nuclear contribution (see Fig.1a). The amount of information that may be extracted is limited by the fact that the zero-field pattern also contains an isotropic magnetic contribution. Nonetheless, one can measure the difference in the scattering perpendicular and parallel to the applied field, which may be modelled. This is derived from the amplitude of curves such as that in Fig.1b, showing the angular variation of intensity over a narrow range of the scattering vector. For the case of a magnetically saturated sample the intensity along the field direction goes to zero ($\theta = 0$), so the amplitude of the scattering perpendicular to the applied field can be uniquely determined. This was found to be typically 0.1-1% of the total small angle scattering.

RESULTS AND DISCUSSION

In Fig.2a are example data for the magnetic scattering from the sample in an applied field of 1.46 T, which is not quite sufficient to saturate the magnetisation. The solid line is fit to the data of using a model of the general form $I_M = \text{const}. f^2(q)S(q) \sin^2 \theta$, where the function $f(q)$ is a form factor describing the local density of magnetic flux within a magnetic grain (due to the spatially varying

![Figure 1](image.png)

**Figure 1** a) An example of the anisotropic magnetic scattering observed from the active layer after removal of the contribution from the nuclear scattering. b) The intensity within a narrow interval of $q$ for the data in Fig.1a, plotted as a function of the angle $\theta$ between the scattering vector $q$ and the local direction of the magnetisation. As expected the magnetic scattering varies as $I_M \propto \sin^2 \theta$. 
magnetisation), $S(q)$ is the structure factor that models the spatial correlation of the magnetisation on different grains, and $q$ is the scattering vector. This is a reasonable way to model the data given a narrow size distribution of particles that are of similar shape and orientation [3,4]. To simplify the analysis $f(q)$ is chosen to be the Fourier transform of a grain of elliptical cross-section, consisting of two concentric shells. This allows for the possibility that magnetisation near the edge of the grains has a different magnitude and direction to that of the central core. This shell model is found to give a much better description of the data over all of the field values measured, from a saturation field of 2.2 T down to a field of 0.45 T corresponding to the closure point of the M-H curve for this material. For simplicity the model assumes that the magnetisation within each shell can be described by an average orientation angle $\theta$, which is valid close to saturation but clearly much less so at lower fields. Nonetheless, fitting the model across the range of applied fields yields remarkable consistency in the length scales extracted, even though the diffraction patterns are very different due to the change in moment orientation.

A slight complication in the analysis arises from the fact that the NiP underlayer is very weakly ferromagnetic, and a change in domain size with applied field gives an additional $q^{-n}$ ($n = 3.4(1)$) contribution to the scattering. This is typical of the Porod scattering expected from randomly distributed inhomogeneities [5], and can be readily observed in the data of Fig. 2b, which shows the scattering from a background reference sample which is identical to the thin film sample under investigation, except that the active CoCrPtB magnetic layer is missing. This additional contribution can easily be distinguished from that due to the active layer due to the simple form, and an additional $q^{-n}$ component is incorporated into the model to account for it. This additional contribution to the much more complex scattering from the active layer can readily be seen by comparing the data to that on a complete sample (Fig. 2a), where it appears as a `linear' contribution to the data at low-q on this

![Figure 2](image-url)

**Figure 2** a) An example of the data from the CoCrPtB medium, at a field of 1.46 T, just below saturation. Evidence of the contribution from the NiP layer can be seen as a `linear' contribution at the lowest q-values, These data reveal information about the grain structure both perpendicular and parallel to the field direction, and indicate that the magnetic grains are elongated. The solid line is a fit to the data using the model described in the text. b) The scattered magnetic intensity arising from the NiP underlayer in a background reference sample without an active magnetic layer. The solid line is a fit to the data (see text).
logarithmic scale. For the case of an applied field of 2.2 T, which is sufficient to saturate the magnetisation, the analysis is relatively straightforward, since the magnetic scattering along the field direction goes to zero. Fits to the data using the shell model indicate a core magnetisation that is significantly greater than that of the outer shell. More surprisingly, the extent of the magnetic core (ca. 3.6(1) nm) is much smaller than that of the total magnetic grain (ca. 10.6(4) nm), the latter agreeing with the value for the physical grain size of 11 nm as determined by transmission electron microscopy (TEM). The spatial correlations are modelled using a Percus-Yevick model for interacting hard spheres [6], which yields an inter-particle separation of 10.8(3) nm, consistent with the diameter of the grains. A schematic of these results is given in Fig. 3a.

Since at saturation the scattering goes to zero along the field direction, no information is available concerning spatial variations parallel to the field. By reducing the field slightly from saturation, transverse components of the magnetisation are allowed to develop which give a contribution to scattering both parallel and perpendicular to the field. In Fig. 3b the same data and fit as plotted in Fig. 2a are plotted on a linear scale, showing that, interestingly, the intensity becomes negative over certain regions of q. This reflects the fact that the quantity being plotted is the difference, at a given q, between the magnetic scattering perpendicular and parallel to the field, and the latter is non-zero at fields below saturation. The model therefore describes more detail than is apparent from just plots of the modulus of the intensity given in Fig. 2a. The latter is nonetheless useful, since it emphasises the quality of the fit over five orders of magnitude. The fits at this and other fields reveal information about the orientation and anisotropic size of the magnetic grains. In this case the model yields a

Figure 3 a) A schematic of the magnetic grain determined at a saturating field of 2.2 T. The magnetic grain dimensions for this field can only be determined along a direction perpendicular to the field, and are rather similar to those found at lower fields. The average grain size is given by the fits to the form factor, and the separation of 10.8 nm is given by the Percus-Yevick structure factor. The elongation of the grains along the field direction, in the approximately ratio drawn, is given by the fits to data at lower fields. b) The same data as that of Fig. 2a, taken at 1.46 T, but represented on a linear scale. Notice that the intensity appears to be negative over some range of q. This reflects the fact that the data are the difference between the magnetic scattering perpendicular and parallel to the field, and the latter is non-zero away from saturation. The solid line is the same fit as in Fig. 2a, which reveals information about the orientation and anisotropic size of the magnetic grains. c) The inset is an expanded region in which the difference plot of intensity is less than zero.
magnetic grain that is elongated along the field direction, with average inter-particle separations of ca. 11.5(5) nm and 10.4(4) nm along directions perpendicular and parallel to the field direction. The occurrence of the much smaller, anisotropic inner core is much more apparent at fields below saturation, and gives rise to some of the sharp features in the magnetic scattering of Fig. 2a. The fits yield an inner core of dimensions 4.0(2) nm and 6.8(3) nm perpendicular and parallel to the field direction, and similarly an outer extent of 8.8 (5) nm and 14.0(3) nm. These results are in broad agreement with those at both higher and lower fields, showing an elongated magnetic grain with an outer dimension close to that of the physical grain (11 nm), but with a much smaller inner core. The systematic errors on fits to data taken at fields below saturation are likely to be larger than those indicated by the fit results, since the model used is less valid in this regime. The aspects of the model that could lead to systematic errors are a) the assumption of concentric shells, and b) the assumption a well-defined direction to describe average of the local magnetisation. The parameters obtained from fits at lower applied fields are also subject to greater uncertainty, since it is only the difference in scattering that is considered. A more sophisticated analysis of the data using numerical simulations is currently underway.

SUMMARY

We have used small angle neutron scattering to investigate the variation of the local magnetisation in longitudinal CoCrPtB thin film media by analysing the anisotropic component of scattered intensity. There is unambiguous evidence that the magnetisation is much higher within a central core region, which is of much smaller extent than the physical grains. This presumably reflects factors such as the compositional variation across the grains and the reduced effective magnetic anisotropy near the surface of the grains. The elongation of the magnetisation along the field direction is also noteworthy. We find that in these small grain (~10 nm) thin film media the basic magnetic entity has a similar extent to the physical grain size. These results should provide interesting input to modelling of the local magnetic structure of these and related systems.

REFERENCES