Small-angle neutron scattering measurements of magnetic cluster sizes in magnetic recording disks

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We describe small-angle neutron scattering measurements of the magnetic cluster size distributions for several longitudinal magnetic recording media. We find that the average magnetic cluster size is slightly larger than the average physical grain size, that there is a broad distribution of cluster sizes, and that the cluster size is inversely correlated to the media signal-to-noise ratio. These results show that intergranular magnetic coupling in these media is small and they provide empirical data for the cluster-size distribution that can be incorporated into models of magnetic recording. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1571652]

As the areal density in magnetic recording disk drives increases, the noise in the longitudinal recording media is reduced by decreasing the size of the magnetic clusters—small regions of the media that are magnetically coupled together. The cluster size must decrease for higher-density media, since the media noise primarily results from the finite cluster size: The transition between bits (areas of opposite magnetization) is narrower when the clusters are smaller. However, if the cluster size is too small, the media will be vulnerable to undesired thermal instability and consequent loss of the recorded data.[1–3] Presently, cluster sizes are believed to be ≈ 10 nm, but accurate knowledge of the size distribution and even the average magnetic cluster size is, for the most part, lacking. Viable characterization methods either lack adequate spatial resolution (which is 25–30 nm for magnetic microscopies)[4,5] or are indirect magnetic methods,[6,7] although recently soft x-ray resonant scattering has been used to measure magnetic correlation lengths in recording media deposited on special substrates.[8,9] It is often assumed that the cluster size is related to the crystalline grain size of the media, but this has not been demonstrated, and it is not clear if the magnetic clusters match the grains or in fact are larger.[1,7,10,11] Note that for the small grain sizes in present media, the grains are single domain, due to the large energy cost to form an intragranular domain wall. Knowledge of the relationship between cluster and grain size is necessary for understanding how the media structure influences recording properties. Furthermore, it has been shown that accurate simulations of magnetic recording properties require a knowledge of the cluster-size distribution.[10,12–15]

In this letter, we describe small-angle neutron scattering (SANS) measurements of the magnetic cluster size in several recording disks and quantify the cluster-size distribution. We find the distribution of magnetic cluster sizes to be quite broad and that, as expected, the media signal to noise is inversely correlated with the cluster size. A comparison of the magnetic cluster size to the physical grain size shows that, particularly for the more advanced media (able to support higher recording density), the magnetic clusters are only slightly larger than the physical grains, and hence the magnetic coupling between nearby grains is not very strong in these media.

SANS[16,17] provides structural information about inhomogeneities, such as physical grains and magnetic domains, with characteristic lengths of one to tens of nm. The measurements were performed at NG7 30m SANS instrument[18] at the National Institute of Standards and Technology (NIST) using an unpolarized beam with a neutron wavelength of 7 Å and a wavelength spread of 11%. Two sample-to-detector distances were used, one spanning 0.0025–0.03 Å^{-1} and the other 0.025–0.3 Å^{-1}. SANS is caused by both physical and magnetic inhomogeneities, and it was thus necessary to separate these two contributions and isolate the magnetic cluster SANS. This was done with two separate SANS measurements.[19,20] Data were first taken for disks with no applied magnetic field ($B=0$ Oe) in a high noise state (see next). For this, the SANS contains contributions from small-angle scattering of the physical thin-film structure (e.g., grains) and of the magnetic film structure (magnetic clusters), which are termed nuclear and magnetic scattering, respectively. Following this measurement, data were obtained with the media held in a magnetic field of $B=6$ kOe applied parallel to the disk surface (perpendicular to the neutron beam).[21] This field is well above the media coercivity and oriented the magnetic moments of the clusters predominately along the applied field direction. A slight angular anisotropy was observed in the SANS data near $Q=0.01\ \text{Å}^{-1}$, due to incomplete saturation of the media. However, this was small and hence there is minimal magnetic scattering in the 6 kOe data. The desired magnetic SANS is obtained by subtracting the $B=6$ kOe spectra from the $B=0$ spectra. This approach is similar to that of Suzuki *et al.*,[19] who studied thick media films on Kapton and were primarily interested in compositional segregation, and to that of Loeffler *et al.*,[20] who were

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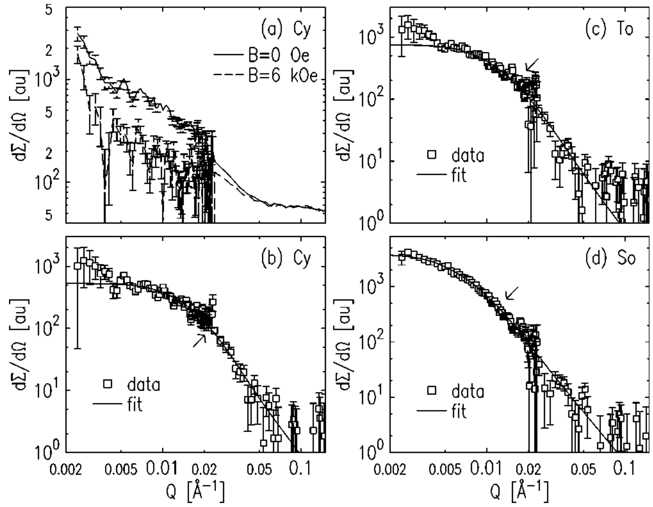

FIG. 1. SANS scattering intensity. (a) Solid line shows data for no applied field ($B = 0$, high noise state), while dashed line shows data for a 6 kOe applied field, which aligns the magnetic moments predominantly along the field direction. (b)–(d) The SANS from the magnetic clusters (squares) for Cy, To, and So, respectively. This is the difference of the $B = 0$ and $B = 6$ kOe scattering intensities [see (a) for Cy]. The line shows the fit to a model assuming a log–normal cluster-size distribution and the arrows mark the approximate break in slope [$\approx \pi/(\text{average diameter})$]. The best-fit average cluster sizes are 14, 16, and 24 nm for Cy, To, and So, respectively, while the best-fit log–normal standard deviations are $\sigma = 0.46$, $\sigma = 0.52$, and $\sigma = 0.56$.

interested in isolated clusters. In a related study, van der Zaag *et al.*[22] used neutron depolarization to investigate the relationship between domain and particle sizes in ferrites with 1–7 μm diam grains.[22]

The magnetic recording disks, which we denote as So, To, and Cy, were identical to those used in three product generations. The magnetic media in each disk was a CoPtCr alloy from 25 to 40 nm thick and these were sandwiched between a carbon layer and one or more nonmagnetic underlayers.[23] All the recording disks had longitudinal media and so the magnetic moments were in the plane of the disks. All disk substrates were glass. The media noise limited signal-to-noise ratio (S_0/N_m) of magnetic transitions was determined by flying an inductive thin-film write head on a spinning disk, writing magnetic transitions spaced 125 nm apart, and reading back the signal and noise using a sensitive read head. The S_0/N_m increased from 28.5 to 31.5 to 34 db for So, To, and Cy, respectively.

For these measurements, it is important that the entire disk is initially ($B = 0$ data set) in a state where the magnetic moments of the clusters are randomly oriented (e.g., a high noise state), since this will result in the largest signal and no artificial correlation. To do this, both recording surfaces of the disk were first fully magnetized in one circumferential direction by scanning the entire surface with the inductive write head held at a constant high magnetic field. Then, the disk surfaces were scanned with the magnetic field from the head oppositely oriented and with a strength approximately equal to the remnant coercivity of the media. This caused approximately half of the magnetic grains to randomly reverse direction, leaving a maximally noisy state. The disks were sliced into eight pieces and stacked to create 16 magnetic layers for SANS measurement.

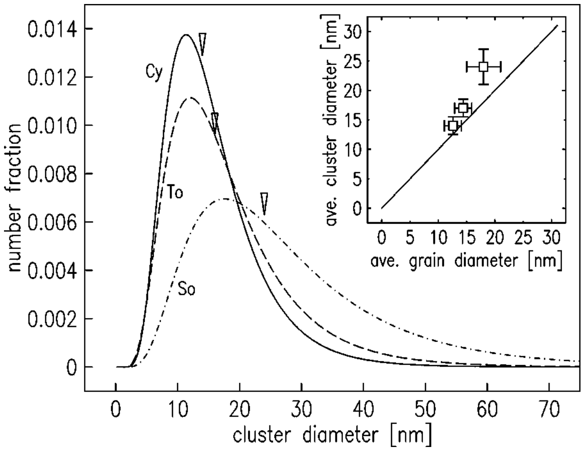

FIG. 2. The solid, dashed, and chain-dashed lines show the best-fit distributions for disks Cy, To, and So, respectively. The arrow heads mark the average cluster size. The inset shows the average magnetic cluster diameter versus the average physical grain diameter as determined by x-ray diffraction and TEM.

Typical data for both fields are shown in Fig. 1(a) (Cy), while magnetic SANS (obtained by subtracting these two spectra) are shown in Figs. 1(b)–1(d). It is apparent that for increasing S_0/N_m (So to To to Cy), there is an increase in the Q where the slope changes (marked with arrows). This qualitatively establishes that the disks with higher S_0/N_m had a smaller average magnetic cluster size. It is also apparent that there is a distribution of cluster sizes, since there are no oscillations in the data and the change in slope is gradual.

To quantitatively model the magnetic SANS, it is necessary to include several effects. The first is interference due to intercluster scattering. However, this is not very important, because there is a broad distribution of cluster sizes (vide infra)[17] and because the scattering from adjacent clusters does not necessarily interfere (the magnetization directions randomly vary). To account for the intercluster scattering, we use the approximate approach described by Pedersen,[24] with small (5%–10%) interference. The second consideration is that the cluster shapes are modeled as cylinders,[16] since transmission electron microscopy (TEM) shows that the physical grains adopt a columnar morphology.[7,23] Finally, it is necessary to include a distribution of cluster sizes.

Our modeling shows that the magnetic SANS data can be well fit using a log–normal distribution of cluster sizes. The best fit cluster-size distributions are shown for the three disks in Fig. 2, while the comparison between the data and fits are shown in Figs. 1(b)–1(d) by the lines. Although other good fits can be found, all reasonable fits yield distributions close to those shown in Fig. 2. Such cluster-size distributions have not been reported before for thin-film recording media; they are the significant result from this letter and allow several important conclusions to be drawn. First, these results show that the media S_0/N_m is inversely correlated with the magnetic cluster size. This is apparent from Fig. 2 when one recalls that S_0/N_m increases from So-To-Cy, and provides firm experimental verification of the models which have proposed that smaller clusters give larger S_0/N_m.[14,15,25]

A second important conclusion follows from a comparison of the magnetic cluster size to the physical grain size, which were obtained from grazing incidence x-ray diffraction[26,27] and TEM. The inset to Fig. 2 shows these results. One can see that the average magnetic cluster size is slightly larger than the physical grain size, and for the most advanced media (Cy) this difference is $\lesssim 10\%$. This result is important as it shows that the intergranular magnetic interactions are not very strong, especially for the advanced media; hence, the size of the media noise sources scale principally with crystalline grain size. This result validates previous assumptions, which have been implicitly or explicitly made in literature.[11,14,15] It is also consistent with other experimental results where indirect methods were used to infer cluster size.[6,7]

It is also important to observe that the cluster size distribution is quite broad. In particular, the log–normal distributions have $\sigma = 0.45-0.55$. This broad distribution is consistent with both the x-ray diffraction and TEM data, which similarly yield broad distributions for the physical grain size, and is consistent with previous observations for other disk materials.[6,11]

Soft x-ray scattering has been used to determine magnetic correlation lengths in CoCr-based recording media that were deposited directly on thin SiN_x substrates without any underlayers.[8,9] These measurements probe similar structural and magnetic correlations to those described herein. However, the x-ray scattering shows strong peaks that are due to interference between well-correlated grains and magnetic clusters, which are absent in our data (see Fig. 1). We believe that this difference is due to the larger coherence length of the x-ray experiment ($\approx 2\ \mu$m) compared to the neutrons (≈ 100 nm).

Recent models of the magnetic and recording properties of thin-film media have begun to include microstructural disorder,[10,12–15] and these have shown that the magnetic cluster (or grain) size distribution has significant effects on these properties, including S_0/N_m. Thus, the exact cluster size distribution is an important component for these models. Our results provide empirical data on this distribution, which, when incorporated into these models, should improve their reliability.

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