Noise characterization of perpendicular recording media by cluster size measurements

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New methodology to obtain reliable correlation between magnetic cluster details measured using magnetic force microscopy (MFM) and noise in perpendicular recording media is reported. In addition to the ac demagnetized state, which is often studied by several researchers, magnetic clusters were examined at two other magnetic states of the recording medium to selectively reveal the thermally unstable and relatively un-reversible clusters that would increase noise and bit-error rates. The proposed method was employed to study magnetic clusters of media samples fabricated at different conditions. Measurements on various samples demonstrated that the MFM can be used to understand the thermally unstable and irreversible clusters in a perpendicular recording medium. A direct correlation between the signal-to-noise ratio (SNR) of the medium measured using spin-stand and magnetic cluster details from MFM images is obtained. The trend can also be used to understand and distinguish the source of noise (such as writing issues or the media microstructure issues).

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Index Terms—Magnetic clusters, Magnetic force microscopy, Medium noise, Magnetic recording media

I. Introduction

Perpendicular magnetic recording technology based disk drives continue to lead data storage industry as areal density progressively increased with substantial price advantage over alternative technologies [1-2]. Achieving higher signal-to-noise ratio (SNR) in perpendicular recording is becoming increasingly important but difficult as the areal density approaches 1 Tbits/in^2 mark. Generally, SNR can be improved by shrinking the grain size and thereby packing more grains per bit area. However, in a granular recording medium, the SNR improvement via grain size reduction alone is limited due to the thermal stability issues and the existence of strong exchange interaction in small grain size media [2-7]. Media noise, including the dominant transition jitter in such exchange coupled or weakly exchange coupled perpendicular recording media is determined by the magnetic cluster size instead of the grain size. Although the media noise can be quickly and reliably measured by spin-stand, the sources of noise cannot be understood using the same. Therefore, alternative techniques such as delta-M measurements [3], first-order reversal curves [7-12] and magnetic force microscopy (MFM) measurements [13-16] have been carried out in the past. Out of these techniques, a systematic inspection of magnetic cluster size and size distribution could aid the media performance optimization process. Previous studies [13-19] revealed a direct correlation between media noise and average magnetic cluster size of the granular recording media.

Magnetic cluster sizes in a perpendicular recording medium depend sensitively on microstructural and magnetic properties of the recording layer materials, interlayer and intralayer exchange interaction, dispersion in exchange interaction and so on [20-22]. The dispersion in grain size and exchange interaction, chiefly due to the oxide grain boundary thickness dispersion, leads to the formation of clusters with a size distribution. Bit error rate (BER) and transition jitter noise of such granular recording medium are determined primarily by relatively larger clusters [1]. On the other hand, clusters with lower thermal stability could flip due to thermal effects and cause issues such as media noise, wide area track erasure (WATER) etc [13]. However, most of the studies as of now focused on the average cluster size measurement using magnetic force microscopy (MFM) at the ac demagnetized state [13-16] to assess the noise level in perpendicular recording media. Although the average cluster size at the demagnetized state does provide some information, key factors related to the media noise could not be retrieved. In this study, cluster size measurements of the perpendicular recording media were carried out at three magnetic remanence states, including the ac demagnetized state, to better correlate the MFM cluster size with medium noise. The method adopted in this study can be used for obtaining supplementary information to better characterize and compare magnetic recording media.

II. EXPERIMENTAL

CoCrPt:oxide based perpendicular recording media, deposited on 2.5 inch glass disk substrates by DC magnetron sputtering were used in this study. The media samples typically include all the key layers of recording media with the exception of the soft magnetic underlayers [1]. Dual ruthenium layers deposited at a lower (bottom layer) and higher (top layer) pressure were used for the required texture and segregation control. Two different kinds of samples, namely Type NC and Type C, were fabricated and characterized. Figure 1 presents schematic illustration of these two types of media structures with approximate layer thicknesses. Type NC sample consists of only a single recording layer of segregated CoCrPt:oxide of thickness 15nm (NC represents no capping layer). In Type C samples a CoCrPtB capping layer was deposited on the granular CoCrPt:oxide magnetic layer to provide a uniform exchange coupling [18]. Type NC and Type C samples with different grain interaction were fabricated by varying the deposition pressure of the top ruthenium and recording layer. In addition, another set of Type C samples (C1, C2, C3 and C4) were fabricated at various deposition conditions to tailor their SNR and to correlate the SNR and the magnetic cluster information. While type C1 is a reference sample, fabricated at an optimum pressure for Ru and recording layers, the samples C2 to C4 were fabricated at higher pressures for Ru and recording layers. The difference between the samples C2 to C4 lies in the thickness of a layer inserted between Ru1 and Ru2. This layer was intentionally introduced to obtain a series of samples with various values of SNR. The magnetic properties of the samples were evaluated by Kerr magnetometer (MOKE) hysteresis loop measurements. Magnetic clusters of the media were inspected at various magnetic states using magnetic force microscope (MFM, Dimension 3100, Digital instruments). MFM images were collected in ambient conditions at a scan height of 10 nm above the disk surface. SNR of disk media were estimated using spin-stand measurements at a linear density of about 875 kfci.

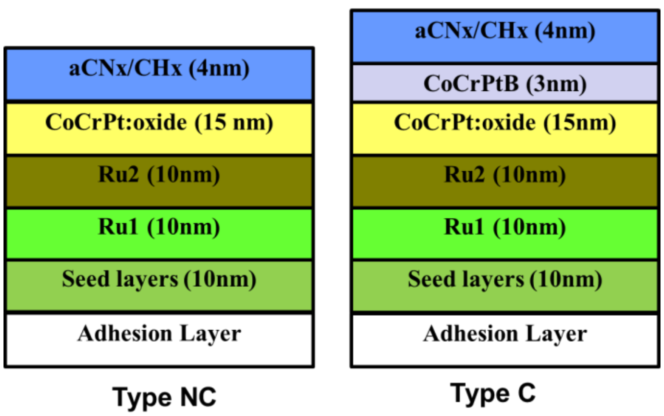

Figure 1: Sketches of the recording media structures with approximate layer thicknesses.

III. METHODOLOGY

Figure 2 shows the three different remanent magnetic states, used for the magnetic cluster size measurements. One of them is the typical ac demagnetized state. The other two remanent states were designed to probe the smaller/low thermal stability and much bigger clusters. For probing lower thermal stability grains/clusters, a saturated sample was subjected to a reverse field (H_{r1}) close to the nucleation field for 10 s at room temperature and subsequently cluster size measurements were carried out at the remanent state (state A). MFM images at this condition could provide information about wide-area adjacent track erasure (WATER) [24]. For probing irreversible clusters that cause BER, the saturated sample was subjected to a reverse field (H_{r2}) close to saturation field for 10 s at room temperature and the magnetic clusters were examined at the corresponding remanent state (state B). MFM images at this condition may reveal presence of clusters that could not be written using the field arising out of the head in a recording process. Magnetic recording media with varying degree of exchange interaction were fabricated by adjusting the deposition conditions/layer structure and cluster size measurements were carried out at the above mentioned magnetic states to understand the variation in the media noise with exchange interaction in a systematic manner. The suitable way to compare media performance based on its absolute values will be; Hr1 ~0.5Hn; Hr2 ~0.95Hs. However, if different media has to be tested for their performance against a particular type of head, it is better to fix the values of Hr1 and Hr2.

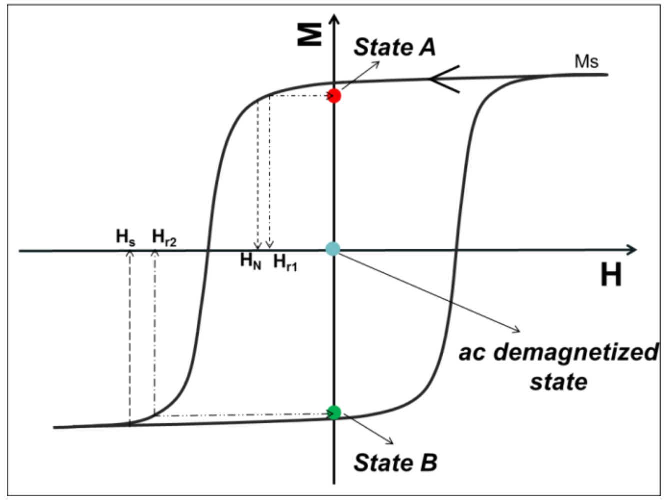

Figure 2: Schematic presentation of the three magnetic states at which MFM cluster size measurements were carried out.

IV. RESULTS AND DISCUSSIONS

A. *Effect of exchange coupling and cluster size*

MOKE hysteresis loops of Type NC and Type C samples prepared at different deposition gas pressure for ruthenium and recording layers are presented in Figure 3. The hysteresis loop of Type NC sample fabricated at a lower pressure (60 mTorr for ruthenium and 35 mTorr for CoCrPt:oxide) exhibits a sharp reversal relative to the samples fabricated at a higher pressure (80 mTorr for ruthenium and 60 mTorr for CoCrPt: oxide layer). The sharp reversal is expected to be due to a larger exchange coupling between the grains in samples which are deposited at a lower pressure. Similar trend was observed in the hysteresis loop of Type C samples deposited at two different pressure settings. In addition, the magnitudes of the nucleation field of Type C samples were found to be higher than that of Type NC samples. The presence of capping layer on top of the granular magnetic layer in Type C samples provide additional exchange coupling and thereby improve the thermal stability [23]. As a result, nucleation field of the recording media is shifted to higher negative values by incorporating the capping layer in the media structure.

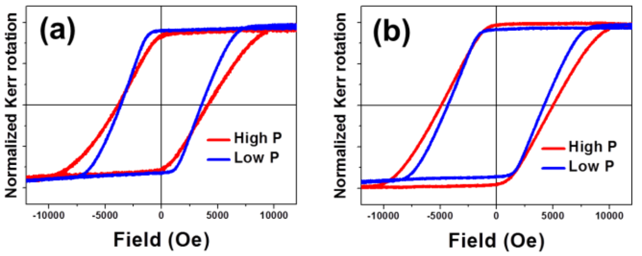

Figure 3: MOKE hysteresis loops of the (a) Type NC and (b) Type C samples fabricated by depositing the second ruthenium and recording layers at a relatively lower pressure (Low P) and higher pressure (high P) conditions.

Different slopes of the hysteresis loop suggest that the grain interaction in Type NC and Type C samples fabricated at different pressure would be different. Due to such difference in grain interactions, the magnetic cluster size and number of magnetic clusters at the aforementioned magnetic states would be different. Therefore, although the results of these samples and their understanding from macromagnetic properties are well known, these samples provide an ideal platform to carry out systematic MFM studies and to compare and correlate these observations against macromagnetic properties.

Figure 4 shows MFM images of the Type NC (Figures 4a and 4b from media fabricated at relatively higher and lower pressure, respectively) and Type C (Figures 4c and 4d from media fabricated at a relatively higher and lower pressure, respectively) samples collected at the ac demagnetized state. Average magnetic domain widths determined by the two-dimensional Fourier transform (2D FFT) method [20] are noted in the respective images (56 nm, 59 nm, 63 nm and 65 nm for Figure 4a-d, respectively). Samples fabricated at a relatively higher pressure consisted of smaller domains in both types of samples. At a higher pressure deposition, the low mobility of the adatoms results in the grain size reduction in the recording layer [26]. In addition, deposition of ruthenium interlayer and CoCrPt:oxide layers at higher pressure enhances the grain segregation and thereby reduce the exchange interaction between the grains [26]. These results are reflected in the formation of narrow width domains in the samples deposited at higher pressure. Notably, Type C samples with capping layers revealed larger domains relative to the Type NC samples fabricated at similar deposition conditions for all other layers. This can be attributed to the additional exchange coupling provided by the capping layer. Although MFM at AC demagnetized states correlates to the known trends of macromagnetic properties, the differences in the MFM images are not significantly distinct to distinguish subtle differences that may be expected between two different media products.

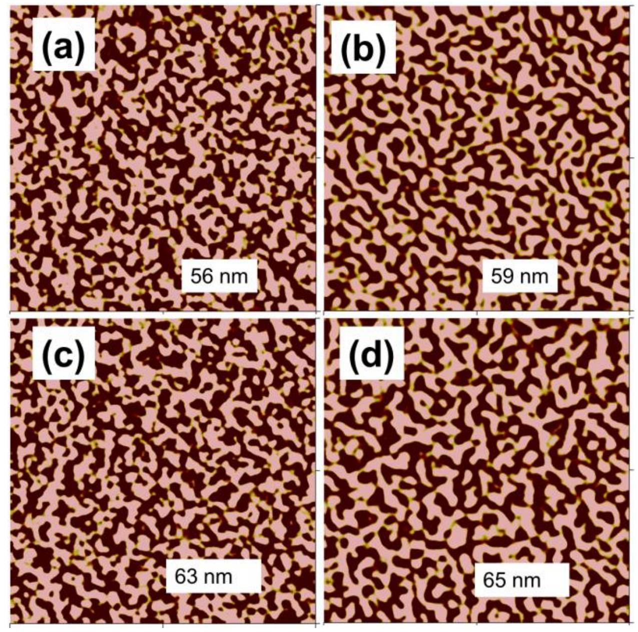

Figure 4: MFM images of Type NC (a-b) and Type C (c-d) sample collected at the ac demagnetized state. The average domain width (in nm) estimated from the 2D FFT method is noted in the respective images. Scan size is 2 μm ×2 μm for all the images.

Typical MFM images of various recording media samples collected at the state A (designed to probe thermally unstable clusters/grains) are shown in figure 5. These MFM images showed several dark spots in a bright background. The dark spots in this case correspond to the reversed clusters. The presence of such reversed clusters could be caused by several possible factors including small grains size, grains with reduced anisotropy (due to stacking faults) or dispersion in the anisotropy orientation. From the MFM images, size of the reversed clusters was estimated by selecting the dark regions by applying the thresholding method [27]. Given the non-circular shape of some of the clusters, area was measured instead of width, in order to represent the cluster size. Table 1 presents the estimated average cluster sizes and number of clusters of Type NC and Type C samples. For Type NC samples deposited at high and low pressure conditions, the number of reversed clusters are 213 and 195 respectively; and average size of the reversed clusters are 1107 and 2225 nm^2 respectively. For Type C samples deposited at high and low pressure conditions, the number of reversed clusters are 192 and 165 respectively; and average size of the reversed clusters are 1319 and 2243 nm^2, respectively. Both Type NC and Type C samples fabricated at a higher pressure showed larger number of reversed clusters with relatively smaller size than the samples deposited at a lower pressure. In comparison with Type NC samples, Type C samples showed a significantly lesser number of clusters at the magnetic state A. Additionally an increase in the average cluster size in Type C samples was also noted. The observed reduction in the number of thermally unstable clusters and increase in the average cluster size can be understood to be arising due to the additional exchange coupling from the capping layer. Thus, these results show the correlation between the measured clusters and the changes in exchange coupling and the usefulness of the proposed methodology.

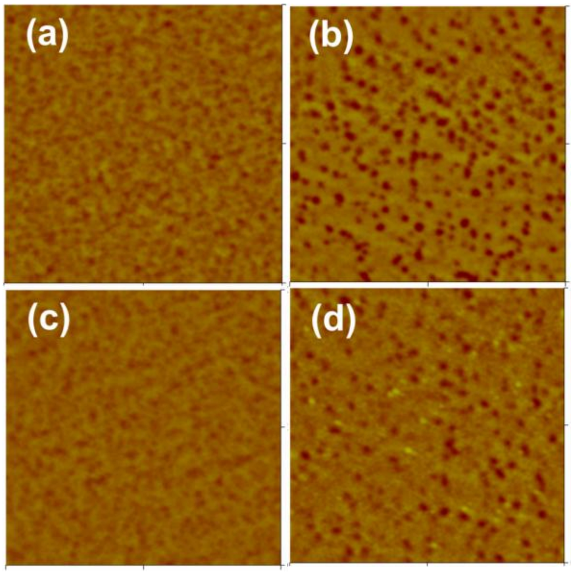

Figure 5: MFM images of type NC (a-b) and type C (c-d) samples collected at the State A. The reversed clusters appear in dark contrast. Scan size is 2 μm ×2 μm for all the images.

The MFM images of the samples were also collected at the state B and presented in Figure 6. The brighter spots observed in these images represent the un-reversed clusters. Appearance of un-reversed clusters is expected from larger grains or strong exchange interaction between the grains or grains with a larger k_uV. From the MFM images, size of the brighter region is assessed and tabulated in table 1. High pressure samples showed lesser number of clusters (127 for Type NC and 154 for Type C) with relatively smaller size (892 nm^2 for Type NC and 1159 nm2 for Type C) at the state B. This is expected as the high pressure deposition leads to the formation of smaller grains with improved segregation. The reduced grain size and weak exchange coupling due to grain segregation results in the formation relatively smaller clusters. Consequently, the number of un-reversed clusters in the state B becomes less. Compared to the Type NC samples, Type C samples revealed more clusters with larger in size at the state B. Since the clusters appearing at the state B may contribute to the BER, minimizing the number of clusters at this state is critical in achieving the desired SNR. To this end, the proposed methodology helps in identifying the nature of recording media and in correlating BER to the clusters observed in state B.

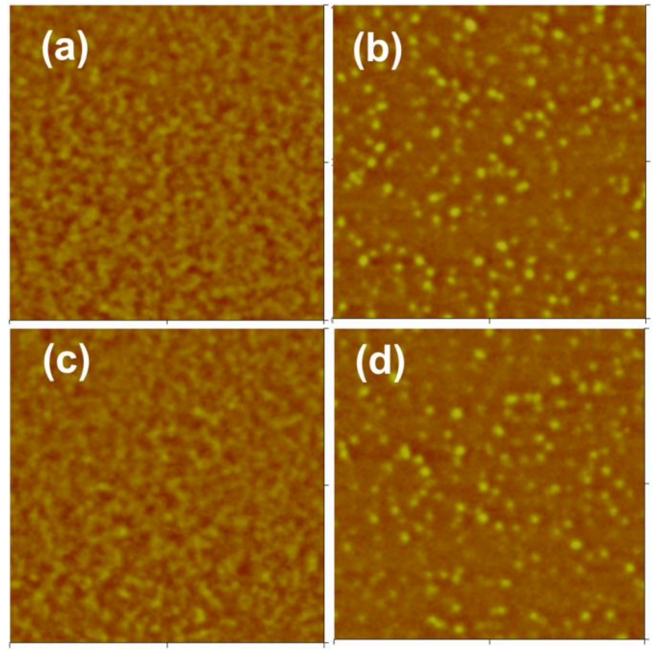

Figure 6: MFM images of type NC (a-b) and type C (c-d) samples collected at the State B. The un-reversed clusters appear in bright contrast. Scan size is 2 μm ×2 μm for all the images.

Table 1: MFM cluster size of the Type NC and Type C media at the state A and state B.

Sample		State A		State B	
		Number of clusters	Average cluster Area (nm^2)	Number of clusters	Average cluster area (nm^2)
Type NC	High Pressure	213	1107	127	892
	Low Pressure	195	2225	154	1800
Type C	High Pressure	192	1319	154	1159
	Low Pressure	165	2243	160	2188

B. *Correlation between SNR and cluster size*

Previous studies [13-16] revealed that average cluster size and cluster size dispersion are strongly correlated with the SNR and media noise. In order to see if the proposed methods in this paper are suitable in correlating SNR with cluster size, we prepared a set of samples with soft magnetic underlayers. Type C media C1, C2, C3 and C4 were fabricated at different deposition conditions to achieve varied recording performance. The difference between these media samples has been described in the experimental section. Using spin-stand, the SNR of these media were measured to be 9.94, 8.64, 8.27 and 8.03 dB, respectively. Figure 7 presents MFM images of media C1 (a-c), C2(d-f), C3(g-i) and C4(j-l) collected at the three different magnetic states. The cluster size and number of clusters estimated from these MFM images are tabulated in table 2. Media with higher SNR (media C1) showed the lowest number of clusters in the State A and State B. Number of magnetic clusters at the state A and state B showed a gradual increase as a function of reducing SNR. Thus relative SNR performance of the media can be readily obtained from the cluster details at the state A or state B. Notably such clear and direct correlation is hard to achieve from MFM images recorded at the ac demagnetized state. These results clearly indicate the advantage of the proposed methodologies.

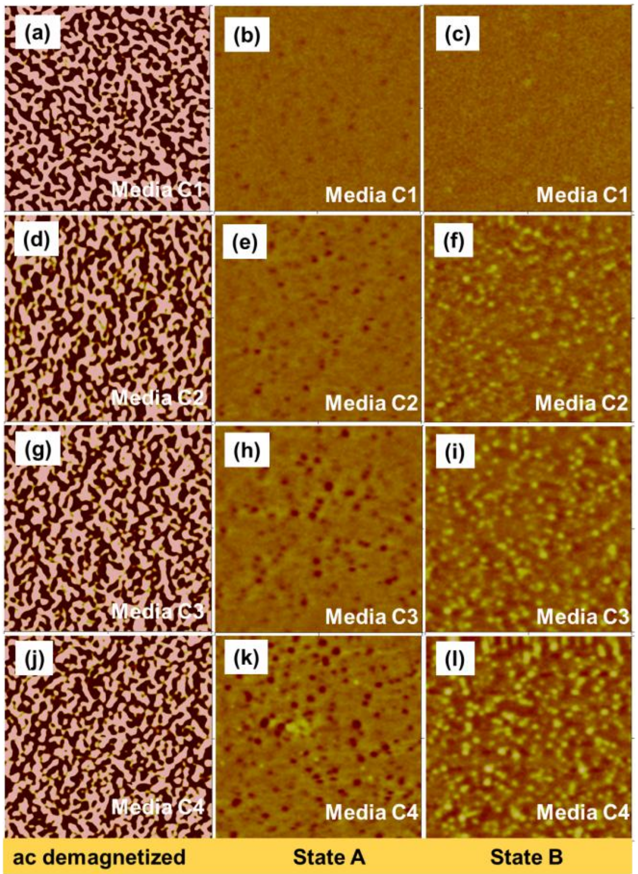

Figure 7: MFM images of the Type C media with soft magnetic layer. Four media samples (C1, C2, C3 and C4) were fabricated at different deposition conditions and MFM image were collected at the three different magnetic states. Scan size is 2 µm ×2 µm for all the images.

Table 2: MFM cluster size and SNR values of Type C media fabricated at different deposition conditions.

Sample	Clusters at State A		Clusters at State B		SNR (spin-stand measurements) (dB)
	Number of clusters	Average cluster Area (nm^2)	Number of clusters	Average cluster Area (nm^2)	
Media C1	25	649	10	747	9.94
Media C2	77	1290	115	1229	8.64
Media C3	100	2095	152	2023	8.27
Media C4	143	2591	189	2699	8.03

A plot of number of magnetic clusters at the state A and state B versus SNR for different Type C samples is presented in Figure 8. SNR of these samples decreased with increase in the number of clusters observed at states A and B. A correlation of SNR with state A would imply SNR drop due to stacking faults or thermal stability issues. However, the number of clusters observed at the state B also showed a correlation on SNR. Correlation of SNR with B suggests two possibilities; The media C2-C4 shows larger clusters due to their deposition conditions or due to a poor writing process. Some of the magnetic and spin-stand test parameters of these media samples are summarized in Table 3 and Table 4. SNR is found to have no correlation with OW, indicating that the writability is not the sole reason behind the poorer SNR or larger number of clusters. It is possible that the changes in clusters and SNR in media C2-C4 could be due to their deposition conditions. These results indicate that the proposed methodology is useful as a supplementary technique in understanding the source of noise in perpendicular media.

Table 3:Magnetic parameters of the Type C media samples

Sample	Hc (Oe)	Hn (Oe)	Hs (Oe)	S*	Ho	$\frac{K_u V}{K_b T}$
Media C1	5096	2270	8713	0.559	7919	67
Media C2	5540	2223	9417	0.548	7941	87
Media C3	5036	1852	9493	0.505	7756	74
Media C4	4856	1635	9621	0.488	7389	80

Table 4: Noise parameters of the Type C media samples.

Sample	MTW	OW2	SNR (dB)
Media C1	3.59	41.5	9.94
Media C2	3.36	31.3	8.64
Media C3	3.55	34.9	8.27
Media C4	3.63	36.4	8.03

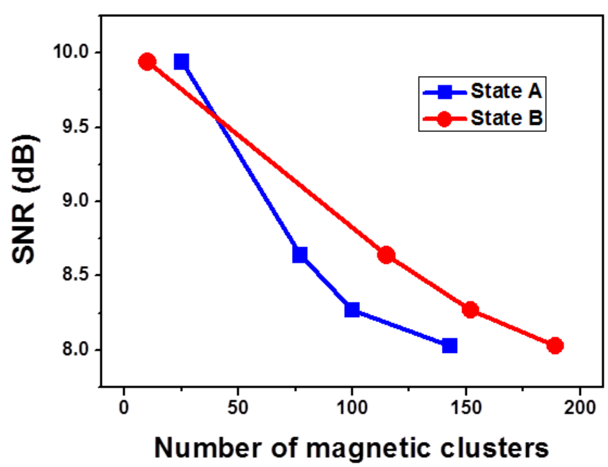

Figure 8: Plot of SNR of the Type C media samples as a function of the number of magnetic clusters revealed at the state A (rectangle) and state B (circles).

V. CONCLUSIONS

This study proposed an improved methodology to obtain magnetic cluster information and the underlying correlation between the perpendicular recording medium noise with its magnetic cluster details. Differing from the previous studies [13-16], magnetic cluster size measurements were performed at three different magnetic states to better understand the noise mechanisms in perpendicular recording media. The method discussed here directly probes the lower thermal stability and irreversible clusters which are the dominant sources of noise in a magnetic recording medium. The discussed technique may help to identify and discern various factors that contribute to the noise in a recording medium.

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