Kinetic Monte Carlo Simulations of *M–H* Loops for HAMR Recording Media: Comparison With MOKE Data

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Our previously developed kinetic Monte Carlo algorithm is used to simulate *M–H* loops of high anisotropy magnetic recording media at long time scales relevant to the experimental measurements using the magneto-optic Kerr effect. Micromagnetic parameters are fit to loop data taken at 300 K and at a sweep rate of 700 Oe/s on a single-layer media developed for heat-assisted magnetic recording. Significantly different fitted parameters result from standard micromagnetic simulations that can access only sweep rates many orders of magnitude faster. Sensitivities of the loops to anisotropy, saturation magnetization, and various distributions are reported.

Index Terms— **Heat-assisted magnetic recording (HAMR), hysteresis loops, kinetic MC (KMC).**

I. Introduction

MICROMAGNETIC modeling as embodied in the Landau–Lifshitz–Gilbert (LLG) equations has evolved to become an important tool for the understanding, evaluation, and design of the magnetic components of a hard drive [1]. One of its more useful applications is in the study of granular recording media for which the basic assumptions of this approach are well suited.

Incorporating the effects of thermal fluctuations through the introduction of a stochastic field term in the LLG equation is used to study a wide range of applications in magnetic media. However, there are limitations imposed by the requirement of picosecond integration time steps to obtain reliable solutions to the LLG equation. This makes the direct study of dynamical magnetization reversal at experimental times scales simply not feasible in many cases. Even with the fastest processors, the overall time period for a simulation is in the order of μs, whereas in the case of experimental *M–H* loops, for example, simulation times of many minutes are required. For systems of non-interacting grains, the dynamics of thermal fluctuation-induced magnetization reversal can be modeled in terms of the Arrhenius-Neel law, which has been used to study the dynamical coercivity in recording media [2]. This concept has also been used as the basis of approximate universal scaling schemes to predict long-time *M–H* loops and signal-to-noise ratio (SNR) decay based on short-time LLG simulation results, with mixed success [3]–[6]. More recently, we have formulated a method based on the kinetic Monte Carlo (KMC) approach that allows for a direct calculation of the long-time behavior of thermally activated systems of interacting magnetic moments [7], [8]. The KMC approach is applied here to simulate $M-H$ loops of high anisotropy granular magnetic thin films for use in heat-assisted magnetic recording (HAMR) applications [9]–[12].

The basic model used in both KMC and LLG methods is the same, namely a description of uniformly magnetized, interacting grains based on an effective field that involves anisotropy, intergrain exchange, magnetostatic interactions, and the external applied magnetic field. The most common technique used to estimate the model parameters for a given system, including the possibility of distributions due to irregularities in the real materials, is to fit simulation results to experimental data on *M–H* loops. Although the experiments can take many seconds to many minutes to complete, as quantified by the sweep rate (R), and are usually performed at room temperature, LLG simulations (often at $T = 0$ K), which span only a few μs at best, are typically used to fit the data to extract the model parameters. These parameters are then used to model other aspects of the recording process, such as bit patterns and media SNR. The overall procedure is therefore critically dependent on the accuracy of the estimates of the model parameters through comparison with experimental, room temperature, *M–H* loops. Given the time scales involved in the experimental *M–H* loops, KMC provides a more accurate estimate of the model parameters than does LLG and is therefore better suited to the overall modeling procedure.

In this paper, we fit micromagnetic model parameters to the experimental data on HAMR media corresponding to a *M–H* loop taken at room temperature using the MOKE, with a (slow) sweep rate of approximately $R = 700$ Oe/s. A similar fit assuming a sweep rate of $R = 100$ Oe/ns, corresponding to a typical LLG time scale, yields parameters, which can differ by about 10%. Sensitivities of key features of the loops, the coercivity (H_c), nucleation field (H_n), and saturation field (H_s) to various model parameters are explored and quantified. The results from these simulations show that all three metrics are most sensitive to the degree of variability in the anisotropy and saturation magnetization.

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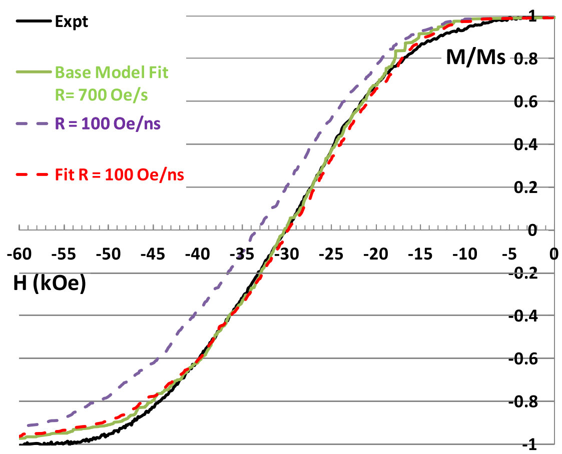

Fig. 1. Experimental HAMR media loop at 300 K and a sweep rate of $R = 700$ Oe/s. Separate fitted simulations were performed at the experimental value of R as well as typical LLG rate of $R = 100$ Oe/ns. Purple: result of using the slow sweep-rate (700 Oe/s) fitted parameters in a fast sweep rate (100 Oe/ns) simulation.

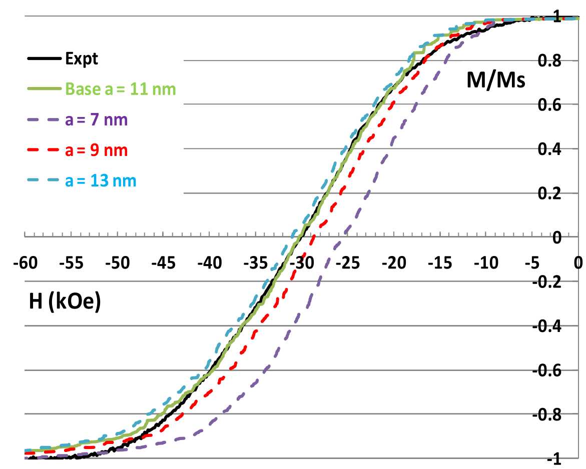

Fig. 2. Impact of lateral grain size dimension (a) on M–H loops.

In the next section, a description of the model parameters is given followed by results for the fitted M–H loops at $T = 300$ K. A discussion of the loop sensitivities to the various model parameters is given in Section III and our conclusion is made in Section IV.

II. Model and M–H Loops

The basic model parameters used in the KMC method are the same as in LLG simulations. A detailed description of the KMC technique is given in [7]. The overall systems size was set to 32 × 32 grains (with periodic boundary conditions) and a thickness of 11 nm. The intergrain exchange stiffness was set at $A = 0.05\ \mu$ erg/cm and a damping constant of 0.1 was used. All other parameters were varied. The best fit to the experimental data (with the field applied perpendicular to the film plane), discussed below, was obtained using parameters that are labeled as base for the remainder of this paper. They are as follows: grain size with lateral dimensions of 11 nm × 11 nm, uniaxial anisotropy $K = 1.67 \times 10^7$ erg/cc, saturation magnetization $M_s = 650$ emu/cc, Gaussian distributions in K and M_s are assumed to be the same, with a standard deviation of 15%. A Gaussian dispersion in the anisotropy direction with a standard deviation of 7^0 is also used. Values for the mean grain size and anisotropy-direction dispersion were estimated from transmission electron microscopy and XRD data. Estimates for M_s and K were derived from M–H loop data. Values used for the magnitude dispersions in these two quantities were based on measured grain-size variations, which can serve to mimic magnetic-property distributions.

Fig. 1 shows the simulation results for fitting the data using the experimental sweep rate of $R = 700$ Oe/s. This was achieved mainly by adjusting K, M_s, and their dispersion. The quality of the fit is seen to be good except for discrepancies close to regions, where M/M_s approaches ±1. The reasons for this difference between the data and simulation results are not known. Effects from higher order anisotropy are also not accounted for in this paper [13], [14]. Also shown in Fig. 1 are results from KMC simulations performed at $R = 100$ Oe/ns using the base parameter values. The higher sweep rate results in a shifted loop with a smaller slope and larger coercivity (from about 30 to 34 kOe), as expected [3]–[6]. A fit was also made to the experimental data using the fast sweep rate by adjusting the base parameter values. Reasonably good agreement was found by changing the anisotropy to a new value of 1.5×10^7 erg/cc and increasing the magnitude (in both K and M_s) dispersion by 16.5%. This result shows the advantage of KMC over LLG simulation in estimating the model parameters through fitting single-layer high-anisotropy media.

III. Sensitivities

In this section, an exploration is made of the sensitivity of the loop shapes to variations in a number of the model parameters. These include the lateral grain size (a × a), M_s, anisotropy axis-direction dispersion, as well as the dispersion in K and M_s. In each of the four figures below, which summarize these results, the experimental data as well as the loop from the base fit (from Fig. 1) are reproduced for comparison.

Fig. 2 shows that the principal impact of changing the lateral grain size is to shift the loop along the field axis. Smaller grains correspond to a smaller value of H_c. The experimental results showing the same effect have recently been reported on FePt films [15]. This may be due to the correlation between the hysteresis, domain structure, and grain size where larger grains can be expected to result in more stable domains. In addition, smaller grains are more prone to superparamagnetic reversal.

A similarly simple effect of variations in M_s is observed in the results of Fig. 3. Changing the saturation magnetization yields a lateral shift in the loops with little impact on the loop shape (e.g., slope). Larger M_s yield smaller H_c, which can be expected based on Stoner–Wohlfarth-type switching, where $H_c \sim H_K = 2\ K/M_s$.

In contrast with the results shown in the previous two figures, changes in the distribution width associated with K

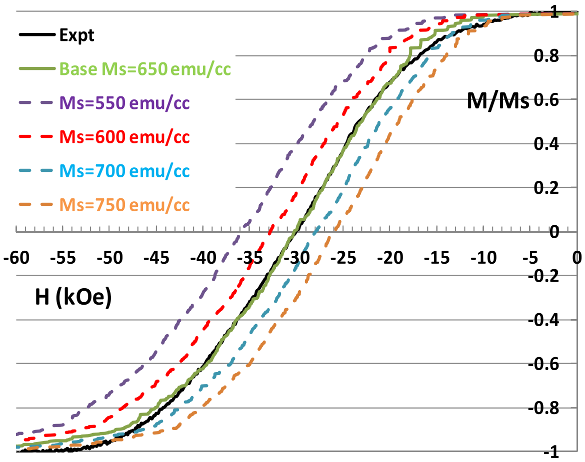

Fig. 3. Impact of variations in the saturation magnetization on M–H loops.

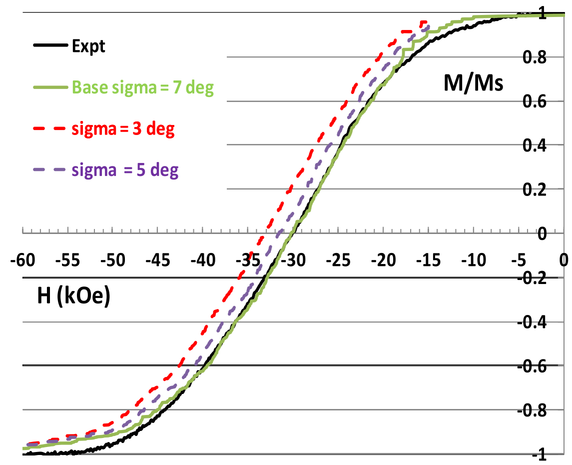

Fig. 5. Impact of varying the anisotropy axis distribution.

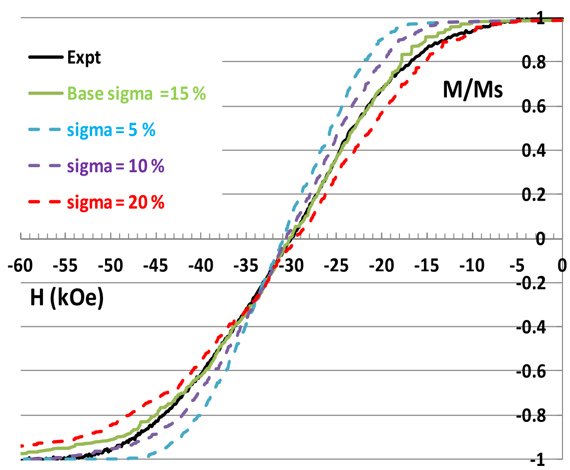

Fig. 4. Impact of variations in the standard deviation as a percentage of K and M_s.

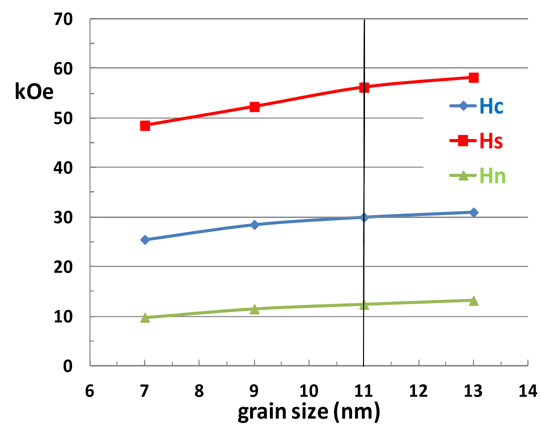

Fig. 6. Dependence of the coercivity H_c, saturation field H_s, and nucleation field H_n on grain size from the results in Fig. 2.

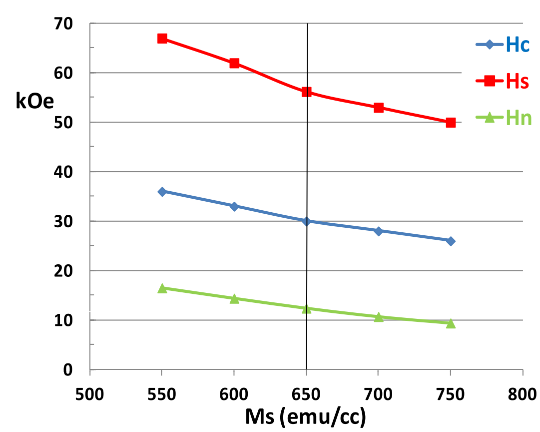

Fig. 7. Dependence of H_c, H_s, and H_n on the saturation magnetization from the results in Fig. 3.

and M_s impact strongly the slope of the $M-H$ curves with little effect on H_c as observed in Fig. 4. As shown below, this effect leads to a relatively large change in the nucleation and saturation fields. A principal source of such distributions in the magnetic properties of real systems is likely due to variations of grain size. The observed modification in loop shapes is linked here to having a more coherent reversal if more of the grains have similar properties as expected with a smaller distribution width.

In addition to control of the grain size, one of the more challenging aspects of high-anisotropy recording media is control of the magnetocrystalline anisotropy axis distribution. Typical values of about 3^0 are common in conventional media [16] but such small values are difficult to achieve in films designed for HAMR applications [17]. Fig. 5 shows our simulation results assuming a smaller distribution and reveals a loop shift to higher coercivity values with little effect on the loop shapes.

A summary of the principal effects of variations in these parameter values is shown in the next four figures. For this purpose, we characterize the loop shapes using H_c, H_s, and H_n. The saturation field was taken to be the field value at which $M/M_s = -0.95$. Similarly, we define the nucleation field at the value, where $M/M_s = +0.95$. The results shown in Figs. 6–9 show that all three field values usually exhibit the same sensitivity as the slopes of these three metrics are roughly the same in each figure. A notable exception is observed in Fig. 8, where H_c is nearly insensitive to the anisotropy and

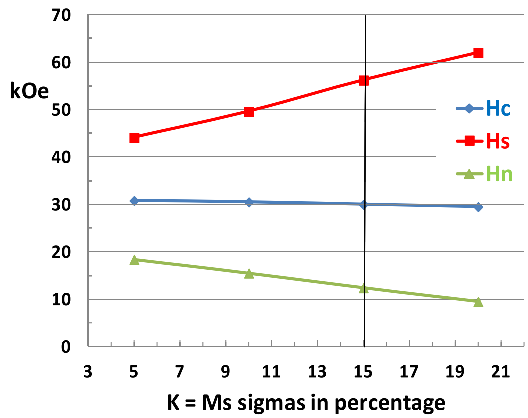

Fig. 8. Dependence of H_c, H_s, and H_n on the standard deviation in anisotropy and magnetization from the results in Fig. 4.

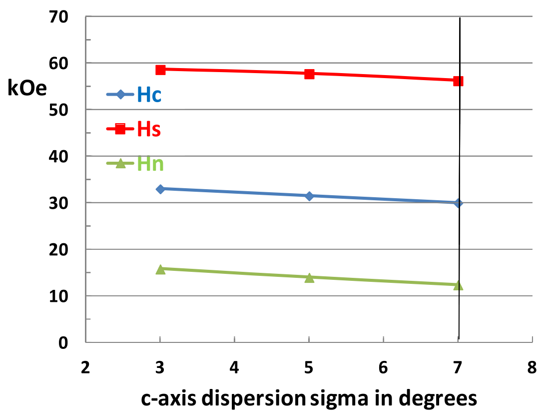

Fig. 9. Dependence of H_c, H_s, and H_n on the anisotropy axis dispersion from the results in Fig. 5.

magnetization distribution, whereas H_s and H_n show large and opposite slopes. Media with these three fields closer in value (giving a square loop) leads to sharper recorded bit transitions and better media SNR [18].

Another notable feature from these four figures is that the saturation field tends to be the most sensitive of the parameters. A large difference between H_s and H_c is not ideal for recording purposes. A higher write field is then required to switch an acceptable fraction the grain magnetizations, which is typically not available. Increasing the write field also can have a detrimental impact on adjacent tracks. In a HAMR recording environment, it can be expected that these three fields decrease approximately the same as the temperature increases.

The tendency from Fig. 6, in which larger grain size yields higher coercivity, is somewhat contrary to the main goal of using the HAMR technology. Smaller grains are desirable for better SNR but need to have a higher coercivity field to prevent thermally induced switching (superparamagnetism). In addition, the results from Fig. 7 show that smaller M_s would enhance H_c, but also increase H_s by an even larger amount. Comparing Figs. 6 and 9, one might conclude that the effects of larger grain size and larger M_s might cancel. A variety of combinations of media parameters could also yield similar M–H loops. Studies of media SNR would be beneficial to estimate the optimal values of grain size and other media parameters, within the limitations imposed by the technology of thin-film fabrication that allow for control of the magnetic parameters.

IV. Conclusion

This paper has demonstrated the utility of the KMC method that gives a direct access to M–H loops at experimental time scales applied to magnetic recording media developed for HAMR applications. A feature of this method is that it uses the same micromagnetic parameters and includes the same interactions as in typical LLG simulations but provides a more reliable estimation of these parameters and their distributions by fitting the simulation results to experimental loop data at the appropriate temperature and sweep rate. This is useful for the subsequent application of recording models based on micromagnetic simulations, which relate microscopic media parameters to key metrics such as long-term SNR decay of a bit pattern [7].

For the comparison with M–H loop data for HAMR recording media performed in this paper, it is clear that the most effective optimization would be through smaller magnitude distributions in K and M_s, as controlled mainly through grain-size distribution. This yields larger H_c as well as a more square loop, which are features associated with better recording characteristics for HAMR applications. Variations in other parameters studied here, grain size, M_s and easy-axis distributions, results mainly in an overall loop shift. The KMC method can also be used for a more comprehensive study of recording media relating other magnetic and microstructure to loop shapes and key recording metrics that provide guidance for avenues of experimental optimization.

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