The mechanical response in a fluid of synthetic antiferromagnetic and ferrimagnetic microdiscs with perpendicular magnetic anisotropy

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In this article, we demonstrate the magneto-mechanic behavior in a fluid environment of perpendicularly magnetized microdiscs with antiferromagnetic interlayer coupling. When suspended in a fluid and under the influence of a simple uniaxial applied magnetic field sequence, the microdiscs mechanically rotate to access the magnetic saturation processes that are either that of the easy axis, hard axis, or in-between the two, in order to lower their energy. Further, these transitions enable the magnetic particles to form reconfigurable magnetic chains, and transduce torque from uniaxial applied fields. These microdiscs offer an attractive platform for the fabrication of fluid based micro- and nanodevices, and dynamically self assembled complex architectures. © 2017 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).

Magnetic micro- and nanoparticles suspended in a fluid are capable of dynamic self assembly under the influence of an applied magnetic field.1–3 To date, complex self assembly behavior in such systems has been achieved using alternating magnetic fields, often in conjunction with liquid interfacial effects,4 or colloidal building blocks with complex steric interactions.5 The fundamental magnetic building blocks used in colloidal self-assembly work however, have been magnetically simple, usually superparamagnetic or ferromagnetic particles stabilized in solution with surface functionalization. In such systems, observing self organization beyond the one-dimensional chaining of particles requires the engineering of both a complex applied field sequence as well as fluid properties such as surface tension.1,3,4

The use of top-down fabrication techniques enables particles to be engineered using magnetic materials generally associated with the field of magnetic recording. Perpendicularly magnetized materials have gained technological prominence because they offer large data retention times and fast domain wall speeds6 for data storage devices,7 high spin-orbit coupling effects for ultra low power logic and memory elements,8–10 and the possibility of novel logic applications resulting from interparticle chaining.11

The interplay between the interlayer antiferromagnetic coupling and the applied field leads to torques on the magnetization that in thin films can be manifested in transitions such as the magnetization flop.15 In a magnetic particle with a strong uniaxial magnetic anisotropy that is free to rotate in a liquid, these torques may be transferred to the particle itself leading to interesting mechanical behavior under field. Further, a particle with moments that are perfectly antiferromagnetically compensated, may be expected to behave differently under an applied field when compared to a particle with a small net magnetic moment where the net moment will be favored under field. Here we demonstrate numerically and experimentally that novel magnetically driven mechanical transitions (or magneto-mechanic transitions) are enabled in a system of perpendicularly magnetized synthetic antiferromagnetic (SAF), and synthetic ferrimagnetic (SFi) microdiscs when suspended in a fluid, where the reorientation of individual particles in the applied field triggers the formation of different configurations of interparticle chaining.

The magnetic microdiscs are fabricated by the patterning and lift off of magnetic thin films14 formed by antiferromagnetically coupled interlayers of Co90Fe29B20 and have a planar disc shape of 2 μm in diameter. The thin film system is modeled as two perpendicularly magnetized, AF coupled ferromagnetic (FM) layers, where the bilayer system is free to rotate in an applied magnetic field. The energy of the system in a zero temperature macrospin model is written as

\[
E = K_1 t_1 \sin^2(\theta_1) + K_2 t_2 \sin^2(\theta_2) + J \cos(\theta_2 - \theta_1)
- H[M_{s1} t_1 \cos(\alpha - \theta_1) + M_{s2} t_2 \cos(\alpha - \theta_2)].
\]

(1)

The interlayer antiferromagnetic coupling and the applied field leads to torques on the magnetization that in thin films can be manifested in transitions such as the magnetization flop.15 In a magnetic particle with a strong uniaxial magnetic anisotropy that is free to rotate in a liquid, these torques may be transferred to the particle itself leading to interesting mechanical behavior under field. Further, a particle with moments that are perfectly antiferromagnetically compensated, may be expected to behave differently under an applied field when compared to a particle with a small net magnetic moment where the net moment will be favored under field. Here we demonstrate numerically and experimentally that novel magnetically driven mechanical transitions (or magneto-mechanic transitions) are enabled in a system of perpendicularly magnetized synthetic antiferromagnetic (SAF), and synthetic ferrimagnetic (SFi) microdiscs when suspended in a fluid, where the reorientation of individual particles in the applied field triggers the formation of different configurations of interparticle chaining.
information on the thin film layer structure may be found in the supplementary material.

Figure 1(a) shows the vibrating sample magnetometry (VSM) hysteresis loop of a SAF thin film grown on a silicon wafer described by $[\text{Ta}(2)/\text{Pt}(2)]_3/[\text{Ta}(2)/\text{Pt}(2)/\text{CoFeB}(1.2)/\text{Pt}(0.5)/\text{Ru}(0.9)/\text{Pt}(0.5)/\text{CoFeB}(1.2)/\text{Pt}(2)]_2/\text{Ta}(2)/[\text{Pt}(2)/\text{Ta}(2)]_3$ with thicknesses in nm. The saturation magnetization $M_S$ is derived from the saturated magnetic signal along the easy axis. Figure 1(a) shows that the thin film undergoes a spin-flip easy axis switching process at a field $H_{EA} \approx 800$ Oe, with $H_J \approx 710$ Oe, and a coercivity $H_C \approx 90$ Oe, where $H_{EA} = H_J + H_C$. Figure 1(b) shows the VSM hysteresis loop along the hard axis for this thin film with $H_{SAF} \approx 5.70$ kOe.

Figure 1(c) shows a VSM hysteresis loop of a suspension of 2 $\mu$m discs fabricated using the magnetic thin film from Figures 1(a) and 1(b). The magnetic saturation process of the suspension is characterized by a linear magnetization response at low fields, followed by a distinct switch to saturation, at $H_{SAF} \approx 930$ Oe. Figures 1(d)–1(f) are optical microscopy images of a suspension of 2 $\mu$m discs in applied fields of –50, 720, and 1420 Oe, respectively, along the increasing positive applied field sweep branch of the hysteresis loop. The field is applied in the plane of the image in the direction of the black arrows. Figure 1(d) taken at $\approx –50$ Oe shows that the particles are randomly oriented and well dispersed. At such low fields, the AF coupling leads to a negligible induced moment in the particles. Figure 1(e) is an image taken at $\approx 720$ Oe, a field value that corresponds to the linear magnetic response regime on the hysteresis loop in Figure 1(c) (blue arrow). The blue arrows on Figure 1(e) highlight the formation of chains of discs in an edge-to-edge assembly schematically shown in the inset of the figure. Here the physical plane of each disc is aligned with the direction of the applied field. Hence, the net moment of the disc must be aligned along the hard axis of the particles. Figure 1(f) is an image taken at $\approx 1.42$ kOe, a field value in the magnetically saturated regime of the hysteresis loop in Figure 1(c) (red arrow). The red arrows in Figure 1(f) highlight the discs in a columnar-chain assembly shown in the inset of the figure where the surface normal of each disc is aligned with the field direction. The net moment of the disc now must be along the easy axis direction. This change in configuration from Figures 1(e) to 1(f) occurs via an abrupt 90° mechanical rotation of each disc that is clearly observed in supplementary material Video 1.

In Figures 2(a) and 2(b), we use Equation (1) to generate the energy and magnetization versus applied field plots for easy axis (blue), hard axis (red), and rotationally unconstrained global (black) magnetic saturation processes for the
SAF system in Figure 1. A spin-flip transition occurs at $H_J = J_f \approx 710 \text{ Oe}$ along the easy axis, and is shown by a blue arrow in Figures 2(a) and 2(b). The hard axis saturation process occurs via the canting of the two FM moments towards the hard axis direction until saturation at a field value of $H_{Sat} \approx 5.70 \text{ kOe}$. At low fields, the hard axis saturation process is the minimum energy magnetic saturation process, and there is a torque on the particles to align the hard axis to the applied field.\textsuperscript{15,16} At high fields, the easy axis saturated state is the lower energy magnetic configuration. The global energy minimum saturation process shown by the black curves in Figures 2(a) and 2(b) reflects this and explains the two different chaining configurations shown in Figures 1(e) and 1(f). The easy axis saturation process becomes the energetically favorable saturation process at a critical field value of $H_{Sat}^\prime$. The system undergoes a transition from having its moments canted towards the hard axis for $H < H_{Sat}^\prime$, to become saturated along the easy axis for $H > H_{Sat}^\prime$. This is enabled by a 90° abrupt mechanical rotation of the particles. Thus the global energy minimum saturation process, is in fact a combination of the hard and easy axis magnetic saturation processes. The freedom of each SAF disc to rotate in the applied magnetic field leads to the reconfiguration of the chains formed by the discs as they interact via dipolar coupling. These reconfigurable magnetic chains may be interesting for a variety of applications in the manipulation of soft matter systems, particularly relating to magnetorheological elastomers and the actuation of components for soft robotics. We attribute the hysteresis in Figure 1(c) primarily to interparticle interactions in the different chaining configurations observed and discuss this further in the supplementary material. $H_{Sat}^\prime$ as shown by the black arrows in Figures 2(a) and 2(b) is derived analytically in the supplementary material.

Having understood the behavior of perfectly compensated perpendicularly magnetized SAF particles in a fluid, we next explore the behavior of particles with a small moment asymmetry between CoFeB layers. Figure 3(a) shows the easy axis VSM hysteresis loops of a synthetic ferromagnetic thin film described by $[\text{Ta}(2)/\text{Pt}(2)]_5/[(\text{Ta}(2)/\text{CoFeB}(1.2)/\text{Pt}(0.5)/\text{Ru}(0.9)/\text{CoFeB}(\approx 1.21)/\text{Pt}(0.5)/\text{CoFeB}(\approx 1.21)/\text{Pt}(2)]_3/\text{Ta}(2)]_3$. The slight thickness differential between the two layers (≈ 1%) is illustrated in Figure 3(b) by a small, slanted transition around zero field (only the rising field sequence is shown for clarity) for the easy axis saturation process, where the blue arrows highlight the ferromagnetism in this thin film. The step in the transition to saturation shows the variation in the coupling field between each individual SFi motif in this thin film stack due to variations in the growth conditions between each motif. For simplicity, we assume the coupling field of the entire film is that of the motif with $H_J \approx 1.43 \text{ kOe}$, as shown in Figure 3(a). For this thin film $H_{Sat}$ is approximately 9.50 kOe as illustrated in Figure 3(c). We assume that the anisotropy and $M_s$ of each layer is not altered by the small asymmetry in thickness between the magnetic layers.

Figure 3(d) shows the VSM loop of the SFi magnetic particles suspended in a liquid. We observe a linear regime, and a distinct, coercive transition to saturation. Figure 3(e) shows that in a very low applied field of $\approx -50 \text{ Oe}$, the particles are aligned with their easy axis parallel to the applied field (field direction shown by the black arrows), due to the small remnant moment arising from the SFi structure which is not evident in the VSM loop in Figure 3(d) due to the small signal size of this transition. In supplementary material Video 2, we observe a 180° rotation of the particles as the applied field value goes through zero in order to align the small remnant moment in the SFi structure with the applied field. We see in Figure 3(f) that at an intermediate applied field value of $\approx 1.22 \text{ kOe}$, the particles are aligned in an edge to edge chaining configuration with the hard axis in the plane of the applied field. This field value is highlighted in Figure 3(d) with a blue arrow. At high fields, the particles saturate in a face to face chaining configuration analogous to the high field case for the SAF microdiscs. The magneto-mechanic transition that occurs in going from Figures 3(e) to 3(f) is evident in supplementary material Video 2, and the magneto-mechanic transition to saturation that occurs at high fields $H > 1.50 \text{ kOe}$ is evident in supplementary material Video 3.

Figures 4(a) and 4(b) shows the simulated energy plots and hysteresis loops for the easy axis (blue), hard axis (red), and rotationally unconstrained global (black) magnetic saturation processes of the SFi system. Figure 4(c) shows the particle, and moment orientations with respect to the applied fields in three different field regimes. As seen in the inset of Figure 4(a), at very low fields the easy axis saturation process is the
As the field is increased into regime II, a magneto-mechanical transition occurs. In this transition, the energy of both the easy and hard axis saturation processes are higher than that of the global energy saturation process as shown in the inset of Figure 4(a), despite the fact that the magnetic response of the global saturation process appears to be identical to that of the hard axis saturation process as shown in the inset of Figure 4(b). The system achieves this because the easy anisotropy axis (and hence the particle itself) reorients in a continuous rotation away from the field direction as the applied field is increased. This is accompanied by a simultaneous rotation of the two moments in a manner that favors the larger moment in the field direction. This process is illustrated in the schematic in Figure 4(c). We show in the supplementary material that for a high enough degree of ferromagnetism, this regime of continuous magneto-mechanical rotation is extinguished.

As the field is increased into regime III, the magneto-mechanical transition to saturation occurs. In this transition, the disc abruptly rotates to once again align the easy anisotropy axis with the applied field, and the moments undergo a transition to a parallel alignment along the easy anisotropy axis (and the field direction).

In this article, we experimentally observe that magnetic microdiscs made using top-down lithography processes and perpendicularly magnetized thin film materials with AF interlayer coupling display magneto-mechanical transitions in a fluid. We explain the origin of these transitions using a simple macrospin minimum energy model. The behavior demonstrated here is potentially interesting for applications in the fields of soft robotics, fluid based microscale mechanical devices, and dynamic self assembly.

See supplementary material for video files showing the magneto-mechanical behavior discussed here. Further information on the thin film multilayer structure, the existence of hysteresis in the fluid based magnetometry, and the effect on the behavior in the fluid of the degree of moment asymmetry in the SFi particles may also be found here.

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