Adhesion and Chaining of Magnetic Particles

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In xerographic copying and printing, small charged particle of toner about 10 microns in diameter are brushed onto a surface[1]. This technique is called magnetic brush development. The bristles of the brush are not plastic fibers as in a paint brush, but instead are formed of chains of magnetizable particles placed into a magnetic field. The chains form as the particles tend to align in the magnetic field. The control of the shape of this brush is important in optimizing the xerographic process. The structure of the chains is driven by the inter-particle adhesion of these magnetizable particles. We describe here theoretical and experimental techniques we have applied to understanding the microscopic relationships between magnetic particle adhesion and the formation and stability of these chain structures.

We explore a model system characteristic of the magnetic brush development, but amenable to experiments and theoretic simulations. The model system is shown in figure 1. The particles are permanent magnets that sit on a non-magnetic surface, called a sleeve. Below the surface are a series of magnets, with their poles alternatively oriented north and south. In magnetic brush development, the sleeve is rotated so as to bring new toner coated particles into the region where the toner is removed. In order to study the bead structure, we change our frame of reference and move the magnets underneath the sleeve, keeping the sleeve fixed.

The structure that the particle take on the sleeve are determined by the competing magnetic forces. For two magnetic dipoles, the interaction is attractive if the south pole of one particle is atop the north pole of the other, and repulsive if the particles and thus the north and south poles are side by side. This effect tends to make many magnetic particles form chains. A single particle in an external magnetic field will experience a torque until the dipole aligns with the magnetic field. This forces the chains that form to align with the magnetic field. However, if there is a gradient in the external magnetic field, the particle will feel a force tending to move it to the points of the highest field gradient.

For our model magnetic system, the field lines emanate from the north poles and loop over to reenter the south poles of the neighboring magnet. The magnetic field therefore has these key features: (1) it decays in intensity away from the sleeve, (2) it is oriented normal to the sleeve over the center of the magnets, and (3) it is tangential to the sleeve between the magnets. The particles therefore will trace out these field lines as shown in figure 1. However, the ultimate height of the chains is limited by the tendency for the particles to go to higher field regions at the expense of forming chains.

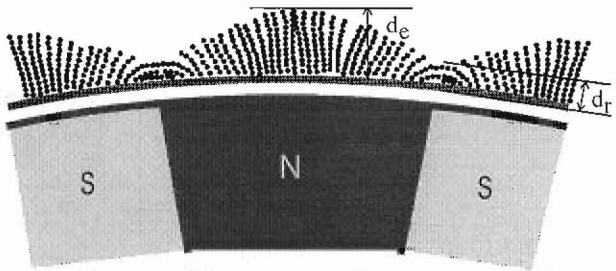

Figure 1: The structure of a magnetic brush

We now consider the behavior of the particles when the sleeve moves relative to the bed. What is seen is that the chains can "walk" to maintain their alignment with the magnetic field lines. This effect is shown in figure 2. Initially (a), the chain stands erect over the center of a magnetic. As the sleeve moves relative to the magnet (b), the chain leans to follow fringe fields towards the neighboring magnet. At the boundary between two magnets (c) the chain lies on the sleeve. As the sleeve

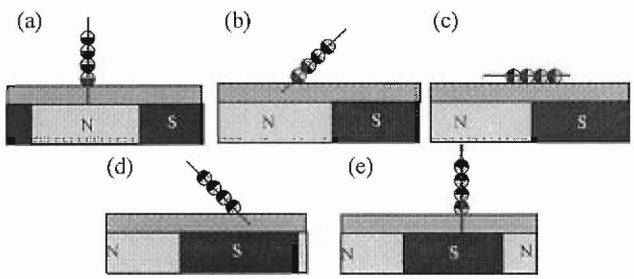

Figure 2: Chain walking

continues to move relative to the magnet (d), the opposite end of the chain lifts up. This process gives walking. When the chain is over the center of the magnet chain, is becomes erect (e). Using a high magnification video camera, we have experimental observed this process. A series of snapshots of the process illustrated above is shown in figure 3. The individual particles on the chain cannot easily be resolved because the chains are coated with the

irregularly shaped toner particles. One can observe the reflection of the chain in the sleeve, so it is easier to access if the chain is erect or reclining. From these images, one can see that the chain stays rigid throughout its rotation, and does not slide along the sleeve. These particular images were taken at quite low speeds (a few seconds for a chain flip). High speed camera images shows that the chains remain rigid up to speeds over 1000 times faster.

We also analyzed images of the packing structure of magnetic particles in cases where enough particles were present to form many closely spaced chains. Some of these images are shown in Figure 4. We found that for thick layers of particles, the length of the chains would decrease as material was removed. However, at a fairly well defined chain length, the removal of more material resulted in fewer chains rather than shorter chains. This supports the idea that there is an energetically favorable chain length for this model system.

The ultimate length of the magnetic particle chains is due to the competition between the particles wanting to be in the high magnetic fields near the sleeve rather than forming longer chains. This tendency can be predicted with a simple analytic calculation. Consider two structures: a single erect chain of N particles sitting over the center of a magnet, and the same N particles sitting on the surface of the sleeve. The potential energy of both structures can be calculated by summing over the dipole-dipole interactions between particles and the interaction between the particle and the external magnetic field. For short chains the erect structure is energetically favorable, but as the chain length increases the side by side structure is favorable. The critical chain length N_c at which this transition occurs, is a function of two ratios; namely r/ℓ and M_s/M_b which are the ratio of the bead radius to the pole spacing, and the ratio of the bead to pole magnetizations respectively. The solution for N_c involves a transcendental equation, which is solved numerically for several values of r/ℓ and M_s/M_b, and show as a contour plot in figure 4.

In practice, there is an energy barrier to a particle moving off the top of an erect chain. The equilibration of chain lengths occurs most likely during chain fragmentation as the chains tumble. Therefore, we have also undertaken a simulation of the chain walking process using quaternion molecular dynamics (QTMD) [2]. Quaternion molecular dynamics, developed for simulating structures in ferrofluids, describes the evolution in time of dipolar systems where the orientation of the particles must be followed throughout the simulation. The particles were modeled as uniform sized spheres, with fixed dipole moments. The simulated magnets, generating the applied field, were moved underneath the sleeve, above which the particles were placed. At each time step, we calculated the force and torque acting on each particle due to the interaction with the external field and the dipole-dipole interactions with neighboring particles, as well as from the non-magnetic inter-particle and particle-sleeve interactions. The linear and angular motion of the individual particles were determined by integrating the equations of motion, considering the mass and inertia of the individual particles, as well as friction effects. This simulation has been highly successful at simulating the formation and breaking of chains.

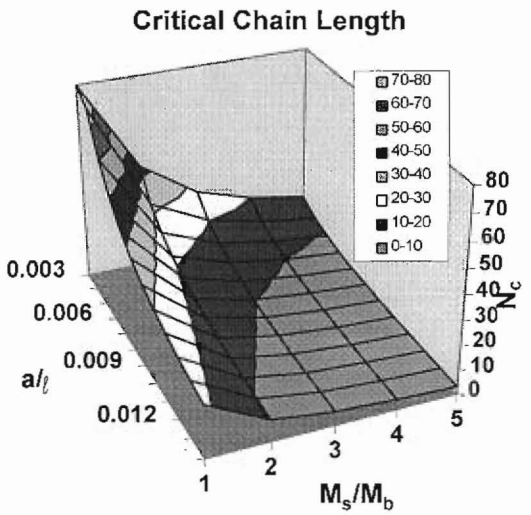

Figure 5. Critical Chain Length

For the magnetic brush simulation, a key component is the interaction with the surface. Experimental, the chain is not observed to slide along the sleeve. The high friction that prevents it from sliding is what gives rise to chain walking. Simulations show that there are extremely high forces tangential to the sleeve surface as the chain is walking. To prevent sliding, a viscous layer was simulated on the surface of the sleeve. In addition, a friction term was added which was proportional to the normal force exerted on the particle by the surface. We found it necessary to keep the viscous layer of finite thickness even with the friction term present. In absence of such a term, a particle that would lift slightly off the sleeve surface would feel no normal and hence no friction force, resulting in its sliding along the surface.

With friction accounted for in this way, we found that the rigid structure of the chain was reproduced during chain walking. Simulations of multiple chains showed that as in ferrofluids, the chains are attracted to each other and will rapidly bundle up and walk collectively. For long chains, we observed that under some conditions the chain would break as it lifted off the sleeve. The chain breaking is highly dependent on the nature of the particle-sleeve interactions. Quaternion molecular dynamics simulations should be able to establish the

maximum typical length of a chain before it breaks in the tumbling process. A comparison between these simulation results, analytical calculation, and the experimentally determined chain height should enable us to relate the microscopic properties of individual particles to the macroscopic chain behavior.

[1] L.B. Schein, Electrophotography and Development Physics, 2nd Ed.(Springer-Verlag, Berlin Heidelberg, 1992).

[2] P. Jund, S. G. Kim, D. Tomanek, and J. Hetherington, Phys. Rev. Lett. 74, 3049 (1995); David Tomanek, Seong Gon Kim, Philippe Jund, Peter Borrmann, Heinrich Stamerjohanns, and Eberhard R. Hilf, Z. Phys. D (1997).

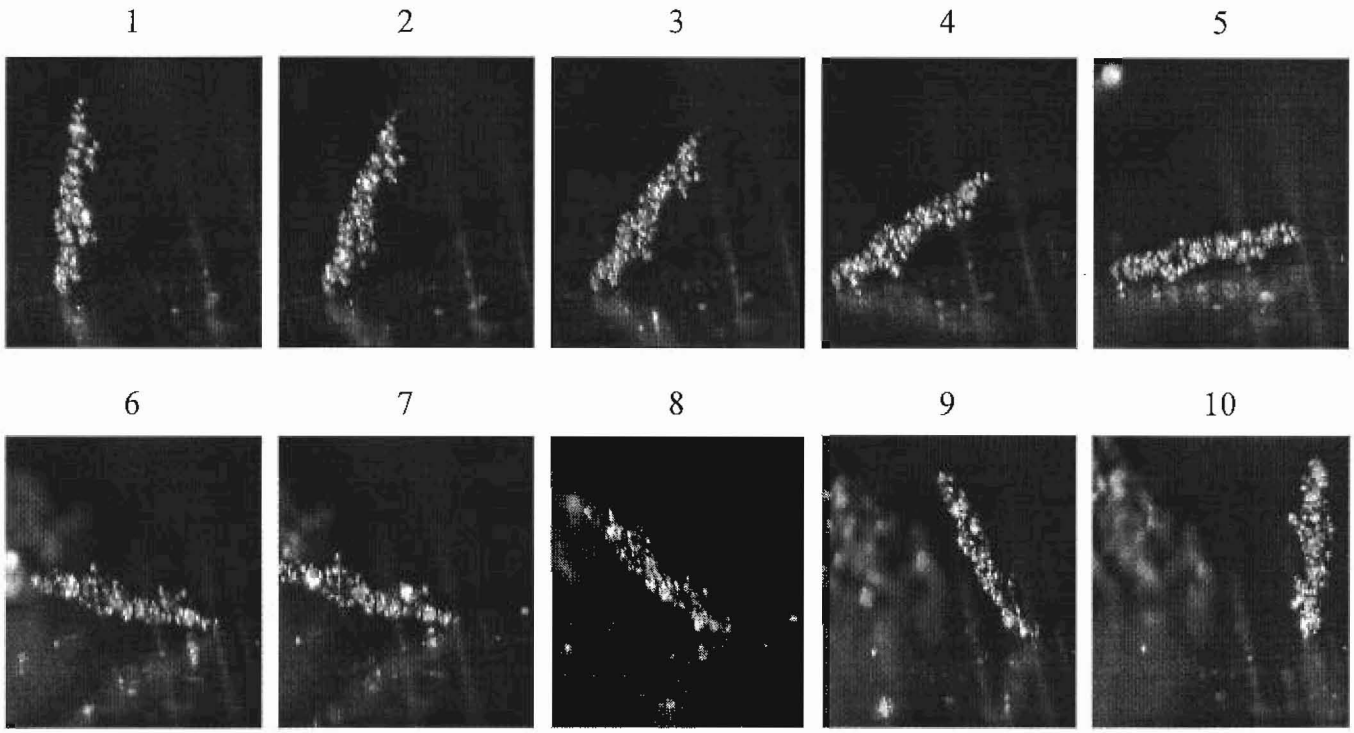

Figure 3: Experimental observation of chain walking.

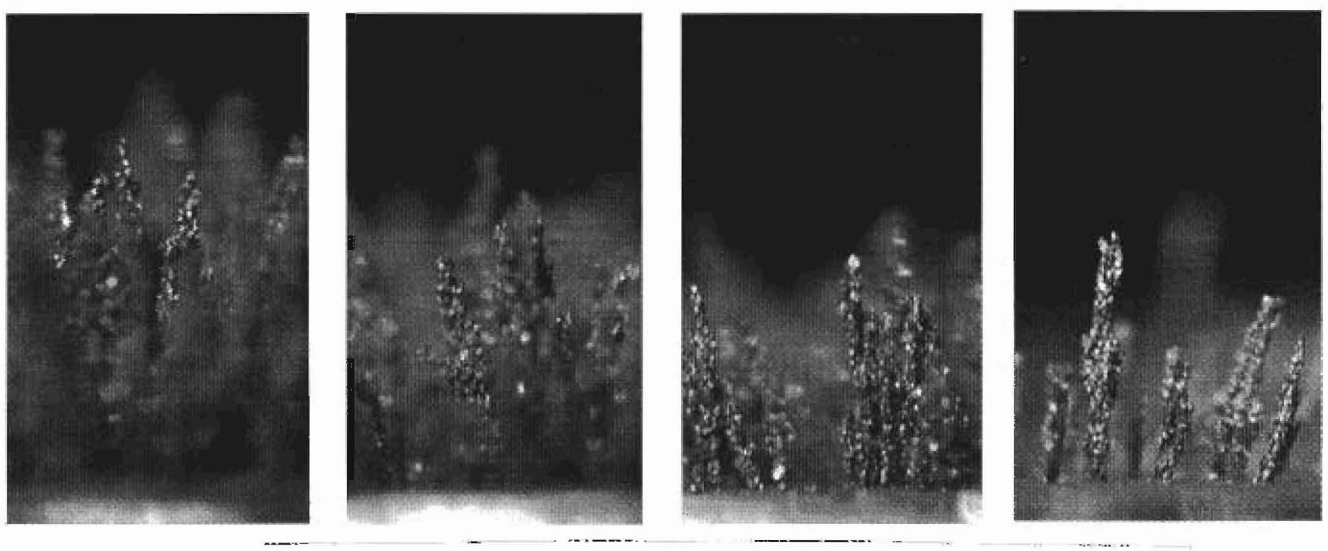

Figure 4: Experimental verification of a statistically favorable chain length.