Dynamics of magnetic microwires suspended in fluids: Magnetostatic forces

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Recibido el 24 de junio de 2010; aceptado el 22 de julio de 2011

We have studied theoretically the interaction between two ferromagnetic microwires as a function of their geometrical parameters, such as length and radii. The analytical results has been contrasted with experimental observations of two amorphous $Fe_{77.5}Si_{7.5}B_{15}$ glass coated microwires (length $L = 3$ mm and radii $R = 7.9$ μm) suspended on the free surface of the liquid (distiller water and ethylene glycol). Then, the resulting dynamics include their magnetostatic interaction and the drag force provided by the viscosity of the liquid.

Keywords: Magnetostatic force; amorphous microwires; magnetostatic interaction.

Hemos estudiado teóricamente la interacción entre dos microhilos ferromagnéticos como función de sus parámetros geométricos, tales como la longitud y el radio. Los resultados analíticos han sido contrastados con observaciones experimentales de dos microhilos amorfos de $Fe_{77.5}Si_{7.5}B_{15}$ cubiertos con vidrio (longitud $L = 3$ mm y radio $R = 7.9$ μm) suspendidos sobre la superficie libre de un fluido (agua destilada o glicol etileno). Luego, la dinámica resultante incluye su interacción magnetostática y la fuerza de arrastre dada por la viscosidad del líquido.

Descriptores: Fuerza magnetostática; microhilos amorfos; interacción magnetostática.

PACS: 75.10.-b; 75.50.Kj; 75.50.Bb

1. Introduction

The integration of biology and the physical sciences at the micro and nanoscales has the potential for impact in many areas of science and technology. One area that is particularly promising is the use of magnetic particles for potential biomedical applications, such as magnetic resonance imaging (the particles can be used to trace bioanalytes in the body), cell and DNA separation, and drug delivery [1]. The trusty sphere remains the preferred shape for particles. Colloidal solutions of spherical particles will spontaneously order into close-packed arrays under appropriate experimental conditions [2-4]. A great effort to understand the self-assembly of spherical semiconductor and metal particles with interesting optical [2], electronic [3], and magnetic properties [4]; but this geometry leaves only one surface for functionalization with bioactive ligands, complicating the generation of multifunctional particles.

On the other hand, much less attention has been paid to the assembly and ordering of magnetic wires [5-7]. In principle, these particles can be assembled into arrays and configurations not possible with spherical particles. Wires are good candidates for applying force to cells and biomolecules. For example, Hultgren *et al.* [8] have shown that ferromagnetic Ni nanowires can be bound to mammalian cells and, in some cases, outperform the commonly used superparamagnetic beads in cell sorting applications. Due to their large aspect ratios, these particles have large remnant magnetizations, and hence can be used in low-field environments where the superparamagnetic beads do not perform at all. Besides, it is possible to modulate precisely the composition along the length of the particles, which in turn enables precise control of their architecture and magnetic properties [9-10]. In addition, by using ligands that bind selectively to different segments of a multicomponent particle, it is possible to introduce spatially modulated multiple functionalization in these systems. In this way magnetic structures could provide an unconventional solution to several research problems and a useful vehicle for imaging and drug delivery applications.

We recently reported analytical calculations for the magnetostatic interactions between pseudo-one-dimensional structures (wires and tubes) [11]. However, an intrinsic obstacle in the experimental study of magnetic interactions is the fact that it is extremely difficult to single out an individual magnetic element, even using the most sensitive magnetometric techniques. Thus, a very interesting macroscopic analogous has been extensively studied, placing together two ferromagnetic amorphous microwires [12]. Two types of soft magnetic microwire families are currently studied: in-water quenched amorphous wires with diameters of around 120 μm [13], and quenched and drawn microwires with diameters ranging from around 2 to 20 μm [14], covered by a protective insulating glassy coat. Bi-stable microwires are characterized by square-shaped hysteresis loops defined by the abrupt reversal of the magnetization between two stable remnant states [15]. Thus, we are interested in observe if amorphous microwires suspended in fluid solution can be oriented and assembled with magnetic fields. Although the dynamics between ferromagnetic wires could in principle seem a quite simple problem to study and model, it is striking to notice how complex this problem can turn out to be. As a first approximation we assume that viscous drag and magnetostatic interactions are the dominant forces.

In this paper we present an analytical model that allows us to investigate the dynamics of ferromagnetic microwires suspended in fluids. Additionally, experimental data for amorphous microwires will be compared with this analytical model. The geometry of the wires is characterized by their radii R and length L. The separation between the wires is written in terms of their axial separation, s, as shown in Fig. 1. Our model goes beyond the dipole-dipole approximation and leads us to obtain an analytical expression for the force in which the geometry of the particles is taken into account.

2. Experimental details

The experimental measurements have been performed in glass coated amorphous bi-stable magnetic microwires with nominal composition $Fe_{77.5}Si_{7.5}B_{15}$, with a saturation magnetization $M_0 = 1.2 \times 10^6$ A/m, radii of $R = 7.9$ µm, and the thickness of the glass coating of $t = 4.1$ µm. They are fabricated by means of Taylor-Ulitovsky technique by which the molten metallic alloy and its glassy coating are rapidly quenched and drawn to a kind of composite microwire.

The morphology of individual microwires (see Fig. 1) was investigated by a inverted microscope (Olympus IX81). The hysteresis curves were measured on a specially designed vibrating sample magnetometer, inserted within a pair of Helmholtz coils. These coils have sufficient field to saturate the wires and present the advantage of field homogeneity and the absence of remnant fields. We will focus our attention on measurements performed at room temperature because a low temperature there is a change in the domain structure of the microwires, probably owing to the increasing internal stresses induced by the different thermal expansion coefficients of the ferromagnetic alloy and the covering glass [16].

The dynamics of magnetic microwires suspended in fluids was investigated by a magnifying glass (Olympus SZ61). We present the details of chaining two microwires, with lengths $L = 3$ mm, suspended in a liquid that come together across an initial separation in a time determined. Four frames from this process are shown in Fig. 2. Microwires suspended in low viscosity liquids (water) precipitate from the solutions

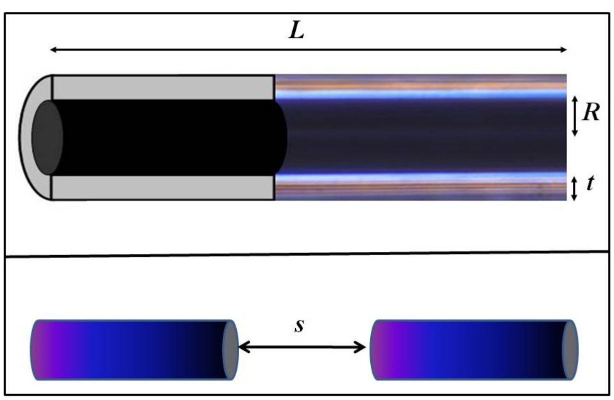

FIGURE 1. (Top) Schematic of the coated microwire contrasted with a phase contrast microscopy image of the $Fe_{77.5}Si_{7.5}B_{15}$ amorphous sample. (Bottom) Axially aligned microwires separated at a distance s.

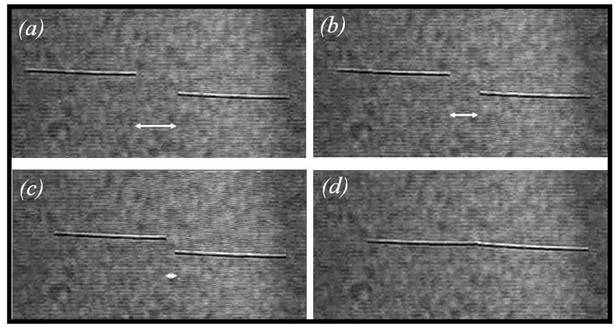

FIGURE 2. Microscopy images showing attractive interaction between two microwires, coaligned in a 30 G external field in an ethylene glycol suspension.

in the course of several minutes. Besides, aggregation occurs due to interwire magnetic forces. To minimize aggregation and precipitation, the microwires were suspended in a more viscous media (ethylene glycol). This suspension is much more stable.

3. Theoretical calculations

We adopt a simplified description of the system, in which the discrete distribution of magnetic moments is replaced with a continuous one characterized by a slowly varying magnetization $\vec{M}(\vec{r})$. Now, it is necessary to specify the functional form of the magnetization for each microwire. Due to their geometry and in order to reduce the stray field, microwires present what is called a mixed configuration [17,18]. This state presents a uniform magnetization along the middle region of the wire, and near the lower and upper surfaces the magnetization deviates from uniformity. This nonhomogeneity produces a decrease of the interaction energy felt by one microwire due to the other. For $L \gg R$ this decrease is small and can be neglected to simplify the calculations [18]. Thus, we consider wires with an axial magnetization defined by $\vec{M}_i(\vec{r}) = M_s\hat{z}$, where $\hat{z}$ is the unit vector parallel to the wire axis. The magnetostatic interaction between wires can be calculated from [19]

$$E_{\text{int}} = \mu_0 \int \vec{M}_2(\vec{r}) \cdot \vec{\nabla} U_1(\vec{r})\, dV$$

where $\vec{M}_2(\vec{r})$ is the magnetization of wire 2 and $U_1(\vec{r})$ is the magnetostatic potential of microwire 1. Thus, the magnetostatic interaction energy between two identical microwires using the magnetostatic field experienced by one of the wires due to the other is given by

$$E_{\text{int}} = -\mu_0 M_s^2 \pi R^2 L \int_0^\infty \frac{dq}{q^2} J_1^2\left(q\frac{R}{L}\right) e^{-q\frac{s}{L}} \left(1 - e^{-q}\right)^2.$$

However, amorphous microwires that motivated this work satisfy $R/L = \alpha \ll 1$, in which case one can use that

$J_1(\alpha x) \approx \alpha x/2$. With this approximation, the interaction energy can be written in a very simple form as

$$E_{\text{int}} = -\frac{\mu_0 M_s^2 \pi L^2 R^4}{2s(L+s)(2L+s)}$$

Finally, a couple of magnetic microwires can attract or repel each other upon approach depending on their relative orientations. For the microwires investigated the interacting magnetic force is given by $\vec{F} = -\vec{\nabla} E_{\text{int}} = F_x \hat{\imath}$, where

$$\vec{F} = -\mu_0 M_s^2 \frac{\pi R^4}{4}\left(\frac{1}{s^2} - \frac{2}{(s+L)^2} + \frac{1}{(2L+s)^2}\right)\hat{\imath}$$

4. Results and discussion

Figure 3 shows the hysteresis loop for an amorphous microwire measured at room temperature. As observed, the magnetization process takes place in one step, defining a square-shaped hysteresis loop corresponding to a bi-stable system.

Figure 4 illustrates experimental data for the separation versus time of pairs of microwires, as the ones shown in Fig. 2, coaligned with different external fields of $H = 5$ G, $H = 10$ G, and $H = 30$ G, created using a pair of Helmholtz coils, in (a) water and (b) ethylene glycol suspension, respectively.

Since the isolated microwires align parallel to the external field, their tendency to aggregate in a random way due to the complicated angular dependence of the magnetostatic forces between randomly oriented microwires is prevent, and instead the interwire interactions cause the wires to form head-to-tail chains along the magnetic field lines. The dynamics is characterized by an initially slow relative motion that speeds up dramatically as the separation closes. The use of higher viscosity solvents such as ethylene glycol results in slower wire motion over comparable distances.

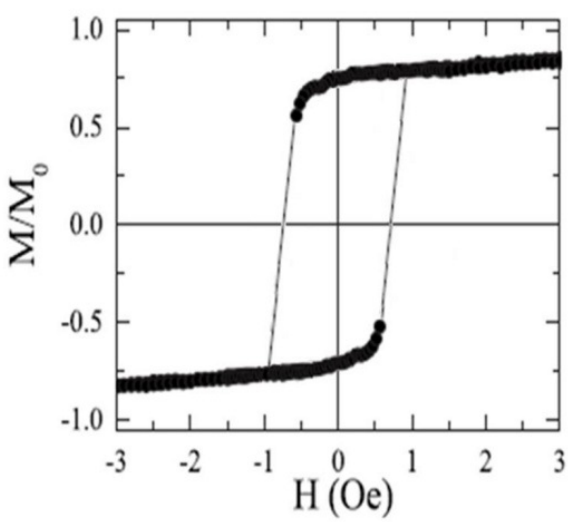

FIGURE 3. Magnetic hysteresis loop measured for an amorphous microwire as the described in the text.

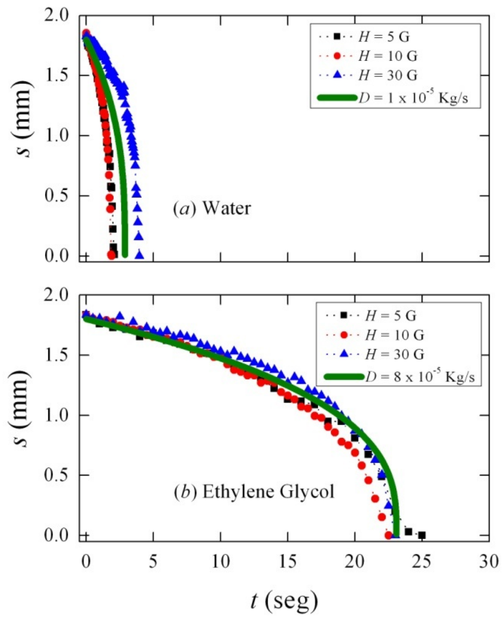

FIGURE 4. Separation versus time for pairs of microwires as the ones shown in Figure 2. The amorphous microwires were coaligned with different external fields in (a) water and (b) ethylene glycol, respectively.

For microparticles in fluid suspension, viscous drag dominates all hydrodynamic effects [20]. Thus, in response to an applied force $\vec{F}$, a particle obtains a velocity $\vec{v} = \vec{F}/D$, where D is the appropriate drag coefficient. This relationship holds for particles moving under gravitational, electric, or as in our case, magnetic forces [21]. This resulting equation of motion may be integrated numerically to obtain the inverse of $s(t)$, $t(s)$. This one-parameter model gives an excellent account of chaining events for amorphous microwires as those in Fig. 4. For the case when our microwires are suspended in water, we obtain the green solid line using $D = 10^{-5}$kg/s, and for our microwires suspended in ethylene glycol, we use $D = 8 \times 10^{-5}$kg/s.

5. Conclusions

In conclusion, we have demonstrated that it is possible to control the self-assembly of magnetic microwires from a liquid suspension with small external magnetic fields. The dynamics of chaining microwires in fluid solution is quantitatively understood using a theoretical model that assumes viscous drag and magnetostatic forces are dominant. This model allows accurate predictions of microwires dynamics in magnetic fields and an estimate of the drag coefficient.

Acknowledgements

This work was supported by FONDECYT grant numbers 11070010 and 1080164, Financiamiento Basal para Centros Científicos y Tecnológicos de Excelencia, and Millenium Science Nucleus under Project P06-022-F.

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