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Field-dependent phase diagram of the structural pattern in a ferrofluid film under perpendicular magnetic field

Chin-Yih Hong^{a,*}, Chih-Hao Lin^a, Chun-Hui Chen^b, Y.P. Chiu^b, S.Y. Yang^{1b},
H.E. Horng^b, H.C. Yang^c

^aDepartment of Mechanical Engineering, Da-Yeh University, 112, Shan-Jeau Rd., Dah-Tsuen, Changhwa 515, Taiwan

^bDepartment of Physics, National Taiwan Normal University, Taipei 116, Taiwan

^cDepartment of Physics, National Taiwan University, Taipei 106, Taiwan

Abstract

Influences of both the magnetic field strength H and the sweep rate dH/dt on the structural pattern evolution in a magnetic fluid film under perpendicular fields are systematically investigated. When the magnetic field is increased at a given rate, the structure evolves from a monodispersed state to a disordered one, then to the first-level ordered hexagonal structure, and finally to the second-level ordered structure through a transition state. With a higher dH/dt , the range of the applied magnetic field corresponding to the first-level ordered structure is widened and the field H_s , at which the transition occurs becomes higher. An empirical power law $H_s \propto (dH/dt)^{0.4}$ was found. A phase diagram for the magnetic fluid film in the H – dH/dt plane is presented. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Magnetic fluid; Hexagonal structure; Phase diagram; Labyrinth pattern

1. Introduction

Pattern formation in magnetic fluid films under magnetic fields has recently received increasing attention both theoretically and experimentally [1–7]. When a thin film of ferrofluid is subjected to a magnetic field applied perpendicular to the plane of film, the structural pattern evolves from a disordered column phase to an ordered structure and then to a labyrinth pattern [3]. The formation of the ordered structure is due to the interaction among columns, whereas the labyrinthine pattern is mainly attributed to the existence of the long-range grain boundaries, which causes contact between columns. If the number of long-range grain boundaries is reduced, the pattern formation is different. In this case, with increasing H , the columns evolve from a disordered column

phase to the first-level hexagonal structural pattern, and finally reach the second-level hexagonal structural pattern through a phase transition [5]. During the transition phase, each column splits into two columns. Among these different structure patterns in a formative process, several critical field strengths can be defined. In addition, the pattern formation was also affected by the sweep rate of the field. Thus, to understand the formative mechanism of the structure pattern, it is necessary to construct a phase diagram in the H – dH/dt plane.

2. Experimental details

A kerosene-based magnetic fluid with a saturated magnetization of 12.5 emu/g was prepared with the co-precipitation technique. The magnetic fluid was injected into a 4 mm × 8 mm rectangular glass cell of thickness 6.0 μm. The uniform magnetic fields were generated by a pair of solenoids. Throughout this experiment, the temperature was kept at 25.7°C by using a circulating water cooler. The applied magnetic field began at zero and was swept up to a final magnetic field H for each data point. The

* Corresponding author. Tel.: 886-4-852-8469 ext 2112; fax: + 886-4-852-9065.

E-mail address: cyhong@mail.dyu.edu.tw (C.-Y. Hong).

¹ Present address: Institute of Physics, Academia Sinica, Nankang, Taipei 115, Taiwan.

photo images of the evolution process of the structural pattern within the magnetic fluid film were taken by using an optical microscope during the charging process of the magnetic field. These photo images were recorded with a CCD video camera. By close observation of these patterns, the structure can be determined. Also, the column sizes were obtained directly from these images while the structural patterns reach equilibrium states at the given magnetic fields and the corresponding column distances were calculated by fast Fourier transformation (FFT) of these images.

3. Results and discussion

The typical structural formative process of a ferrofluid film under magnetic fields perpendicular to the plane of film for lower sweep rates is such that when the field strength H exceeds some critical value, H_0 , the magnetic particles inside the film agglomerate and form particle columns scattered randomly throughout the film. As H increases and exceeds another critical value, H_{h1} , the pattern evolves from the disordered column phase to a hexagonal structure. When H becomes higher than another critical value, H_p , the column distance becomes independent of the variation of the H , and a plateau is formed in the d - H curve at a fixed dH/dt . When H is even higher and exceeds another critical value, H_s , the structural pattern goes through a phase transition in which a column splits into two columns and finally forms a hexagonal structure as the field strength reaches another critical value, H_{h2} . These hexagonal patterns may be characterized by the distance between the two nearest neighboring columns. However, for higher sweep rates, only one level of hexagonal structure was observed. The difference between these two types of behaviors is mainly due to the effect of column size. At a lower sweep rate, the duration of the formative time is longer and the size of the column becomes larger than that at a higher sweep rate in which the formative time is shorter.

Fig. 1(a) gives a typical characteristic distance as a function of the field sweep rate. There are two types of behaviors; one has two plateaus separated by a transition phase for lower sweep rates as those from 2 to 25 Oe/s, and the other has only one plateau for a higher sweep rate of 40 Oe/s. Fig. 1(b) gives the corresponding column sizes, in which behavior similar to that of Fig. 1(a) appears. It must be noted that between field strengths H_{h1} and H_p , unlike the column distance, the column size does not change with an increase of field strength, because new columns with the same size form continuously while the field strength increases from H_{h1} to H_p . Moreover, the ranges of field strength for the plateaus, between H_{h1} and H_p , in both figures increase as the sweep rate increases. It shows that a column of large size resulting from a lower sweep rate is easier to split, due to the

Fig. 1. Plot of (a) the distance between columns and (b) the column size of hexagonal structure in ferrofluid films as a function of field strength at various sweep rates.

competition between the surface tension of a column and the intra-dipolar repulsive force in each column. Thus, for a lower sweep rate, the field range of the plateau is smaller than for a higher sweep rate.

Fig. 2 gives the phase diagram of structural pattern, formed inside a magnetic fluid film under perpendicular magnetic fields, in the $H - dH/dt$ plane. When $H < H_0$, the magnetic fluid is mono-dispersed, and H_0 is independent of the sweep rate. When the $H > H_0$, the magnetic particles of magnetic fluid agglomerate and form magnetic columns that are scattered randomly in the film. As the field strength increases, more and more magnetic columns appear. Until $H = H_{h1}$, a dynamic hexagonal structure forms, and H_{h1} is also independent of the sweep rate. For $H_p > H > H_{h1}$, new columns form continuously and the characteristic distance reduces as the areal density of columns becomes higher. Then, the characteristic distance of the hexagonal structure remains constant regardless of the increase of field strength as $H_s > H > H_p$, and the system is in the state of 1st-level stable hexagonal structure. While $H > H_s$, columns start to split, the structure pattern remains fairly ordered with reduction in its characteristic distance, and the system enters a dynamic hexagonal structure again. This splitting process continues until the field strength reaches

Fig. 2. Phase diagram of structural pattern, formed inside a magnetic fluid film subjected to perpendicular magnetic fields, in the H - dH/dt plane.

H_{h2} . As $H > H_{h2}$, the characteristic distance of the hexagonal structure again remains constant regardless of the increase of field strength and of the system entering the

2nd-level stable hexagonal structure. Unlike H_0 and H_{h1} , H_p and H_s are functions of the sweep rate and follow the power laws of $(dH/dt)^{0.23}$ and $(dH/dt)^{0.4}$, respectively.

4. Conclusion

A phase diagram for the patterns formed inside a ferrofluid film was constructed. Several critical field strengths were defined based on the different structures. H_0 and H_{h1} , which separate the mono-dispersed phase, disorder phase and dynamic hexagonal structure, are independent of the field strength. On the other hand, H_p and H_s , which separate the dynamic hexagonal structure, 1st-level stable hexagonal structure, and splitting process, vary as a power of the sweep rate and the powers are 0.23 and 0.40, respectively.

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