ELSEVIER

Available online at www.sciencedirect.com

SCIENCE @ DIRECT®

Journal of Magnetism and Magnetic Materials 289 (2005) 93–96

Journal of
Mmagnetism
and
Mmagnetic
materialswww.elsevier.com/locate/jmmm

Thermal activated variation in the ordered structures in magnetic fluids films

Chin-Yih Hong^{a,*}, Y.H. Ke^b, H.E. Horng^{b,c}, S.Y. Yang^c, H.C. Yang^d^a*Department of Mechanical and Automation Engineering, 112 Shan-Jeau road, Da-Yeh University, Chang-Hwa 515, Taiwan*^b*Department of Physics, National Taiwan Normal University, Taipei 116, Taiwan*^c*Institute of Physics, National Taiwan Normal University, Taipei 116, Taiwan*^d*Department of Physics, National Taiwan University, Taipei 106, Taiwan*

Available online 26 November 2004

Abstract

A hexagonal ordered structure of magnetic columns is achieved in a highly homogeneous magnetic fluid film under an external magnetic field perpendicular to the film surface. At a fixed temperature, the magnetic columns are stable. When the temperature rises, the columns remain unchanged initially, and then some of them disappear as the temperature exceeds a critical value. Furthermore, all columns disappear when the temperature is further raised. The column disappearance was due to the dispersion of column particles into the liquid at a higher temperature. The critical temperature, at which the column particles start to melt, was found to increase under a stronger magnetic field. The relationships between the critical temperature and the fluid concentration, as well as the film thickness, are investigated. Thus, the role of temperature in the stability of ordered structures in the magnetic fluid film is clarified.

© 2004 Elsevier B.V. All rights reserved.

PACS: 75.50.Mm; 61.20.Ne; 68.60.Dv

Keywords: Magnetic fluid; Ordered structure; Thermal stability

1. Introduction

Studies on structures in magnetic fluid films under external magnetic fields have been attracting the interest of many scientists and engineers because of the rich patterns in these structures. In the 1970s, the agglomeration of magnetic particles in magnetic fluid films under magnetic fields was observed [1]. Rosensweig and Popplewell then theoretically discussed the agglomeration of magnetic particles in magnetic fluid films under external magnetic fields [2]. Later, a series of structural patterns due to the either phase separation [3–5] or the fingering of microdrops [6–8] in magnetic fluid films

under the influence of magnetic fields was reported. It is believed that the kinetic energy of the magnetic particles and the external magnetic field are crucial to the agglomeration process.

In 1997, ordered hexagonal structures formed by magnetic columns in highly homogeneous magnetic fluid films subjected to magnetic fields were discovered by Hong et al. [5]. Also, a multi-level ordered structural evolution was observed [9]. It was further indicated that the ordered structure formation in the magnetic fluid film could be dominated by magnetic field strength, the sweep rate of the field, film thickness and fluid concentration, etc. [10–12]. Since column agglomeration is affected by the kinetic energy of the particles, temperature must also be influential on ordered structure formation in magnetic fluid films under magnetic

*Corresponding author. Tel./fax: +886 4 8511213.

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

fields. To clarify the role played by temperature in the formation of ordered structures in magnetic fluid films, structure evolutions within magnetic fields are investigated at various temperatures.

2. Experimental details

Kerosene-based MnFe_2O_4 magnetic fluid used has a saturated magnetization of 7.7 emu/g . The mean diameter of the particles is 12.4 nm with a standard deviation of 2.4 nm . The magnetic fluid was injected into a $6 \mu\text{m}$ -thick glass cell to form a magnetic fluid thin film. This film was positioned inside a vacuum cell, whose temperature was controlled with a circulating water system [12]. A LakeShore Pt-111 temperature sensor, which was located beside the film, was used to monitor the temperature within 0.1°C . Then, the film, as well as the cell, was subjected to a pair of solenoids, which generated a uniform magnetic field perpendicular to the plane of the film. To obtain an ordered structure in the film, a magnetic field was applied normally to the film and was increased from zero to the desired strength at a given sweep rate and a fixed temperature. Thereafter, the field was fixed at the desired strength. After the structure reached equilibrium, the ordered structure was recorded with the aid of a CCD camera and an optical microscope. The temperature was then increased gradually to a higher value, at which point the temperature was held for 15 min, so that the structure was able to reach to another equilibrium state. The temperature was then increased in this way to a final temperature. Thus, the structural evolution during a heating process under a given field strength was investigated.

3. Results and discussion

To investigate the evolution of an ordered structure in the magnetic fluid film during a heating process, an external field was increased to certain strength, here 120 Oe , at 26.0°C to obtain an initially ordered structure. An image of the structural pattern at equilibrium is shown in Fig. 1(a). As the temperature increased, the structural pattern remained almost unchanged until the temperature exceeded a critical temperature ($= 35.0^\circ\text{C}$ here), at which point the column particles started to disperse into the liquid carrier, and the number of columns reduced. When the temperature rose from 35.0°C , more columns disappeared, and the interaction between magnetic columns was reduced. As the temperature reached 40.0°C , the column–column interaction nearly vanished, and hence the structural pattern evolved to a disordered state, as shown in Fig. 1(c). At temperatures higher than 56.0°C , the influence of the thermal energy completely sup-

Fig. 1. Structural evolution in the magnetic fluid film under a perpendicular field of 120 Oe when the temperature rose from 26°C to 56°C . The $M_s = 7.7 \text{ emu/g}$ $dH/dt = 5 \text{ Oe/s}$ $L = 6.0 \mu\text{m}$.

Fig. 2. Characteristic d - T curves under various values of field strength H . The $M_s = 7.7 \text{ emu/g}$ $dH/dt = 5 \text{ Oe/s}$ $L = 6.0 \mu\text{m}$.

pressed that of the magnetic energy on the magnetic particles. As a result, all the originally agglomerated magnetic particles were dispersed into the liquid, as shown in Fig. 1(d), and the magnetic particles became monodispersed.

To qualitatively describe the structural evolution during a heating process, the structures shown in Fig. 1 are analyzed. As mentioned above, the structural

pattern remained unchanged as the temperature rose from 26.0 °C to 35.0 °C. Hence, a constant value resulted for the average column spacing d of the ordered structure in the magnetic fluid film as the temperature increased from 26.0 °C to 35.0 °C, as shown by the curve for 120 Oe in Fig. 2. This was followed by an increase in the value of d at temperatures higher than 35.0 °C, due to the dispersion of magnetic columns. The temperature at which d starts to increase is denoted by T_m . When the temperature exceeded 40.0 °C, the structure evolved to a

disordered column state, at which the average column spacing became meaningless and was not analyzed. A similar behavior was also found for the thermally activated structural evolution in the magnetic fluid film under various magnetic fields, such as 70, 180, 300 Oe, as shown in Fig. 2. It was observed that the higher the field strength, the higher the T_m . The relationship between T_m and the field strength is plotted in Fig. 3(a). The monotonous increase in T_m with the rising field strength implies that a more stable state was achieved for the

Fig. 3. Phase diagram in the coordinates of (a) temperature and field strength, T - H , (b) temperature and film thickness, T - L , and (c) temperature and fluid concentration, T - M_s . The curve in each figure divides the structure in the magnetic fluid film into two kinds of states: ordered solid-column state and melting-column state.

ordered structure in the magnetic fluid film under a higher field. Thus, more thermal energy is required to change the equilibrium state of the ordered structure in the film.

Fig. 3(a) also denotes a phase diagram for the structure in a magnetic fluid film. For a point at region below the T_m - H curve in the figure, the structure is at a steady ordered state. The columns in the structure hold still like solid columns when the temperature varies slightly. On the other hand, for a point at region above the T_m - H curve, the columns melt when the temperature rises.

In addition to the field strength, the structure formation in a magnetic fluid film is dominated by other control parameters, such as the film thickness, and the fluid concentration. Hence, the film-thickness L and the fluid-concentration M_s dependencies of T_m are examined. The results are shown in Fig. 3(c) and (d), respectively. The T_m slightly decreases with the increase in L , whereas it obviously becomes higher for a concentrated magnetic fluid. By experimental observation on the column spacing of the initially ordered structure in the magnetic fluid film, smaller column spacing was resulted for the structure in a thinner film or a concentrated fluid. Because the column-column interaction is enhanced when the columns become closer, more thermal energy is necessary to disperse column particles into the liquid. This leads to the increase in T_m when reducing the film thickness or increasing the fluid concentration.

4. Conclusion

The ordered structure in a magnetic fluid film undergoes a process of evolution during a heating process: from the initially ordered state to a disordered pattern, and to mono-dispersion state. It is noted that the thermally activated structural evolution depends on several control parameters, such as the magnetic field

strength, the film thickness, and the fluid concentration. These phenomena can be interpreted by considering the competition between the magnetic energy and thermal energy of the system.

Acknowledgements

This work was supported by National Science Council of R.O.C. under Grant Nos. NSC91-2212-E212-010 and NSC91-2112-M003-013, NSC93-2120-M-003-001 and NSC93-2112-M-003-007.

References

- [1] C.F. Hayes, J. Colloid Inter. Sci. 52 (1975) 239.
- [2] R.E. Rosensweig, J. Popplewell, Int. J. Appl. Electromagn. Mater. 2 (Suppl.) (1992) 83.
- [3] S. Taketomi, S. Ogawa, H. Miyajima, S. Chikazumi, IEEE Trans. Magn. 4 (1989) 384.
- [4] Hao Wang, Yun Zhu, C. Boyd, Weili Luo, A. Cebers, R.E. Rosensweig, Phys. Rev. Lett. 72 (1994) 1929.
- [5] Chin-Yih Hong, H.E. Horng, I.J. Jamh, C.J. Hsu, Y.D. Yao, H.C. Yang, J. Appl. Phys. 81 (1997) 4275.
- [6] J.-C. Bacri, A. Cebers, R. Perzynski, Phys. Rev. Lett. 72 (1994) 2705.
- [7] C. Flament, G. Pacitto, J.-C. Bacri, I. Drikis, A. Cebers, Phys. Fluids 10 (1998) 2464.
- [8] I.J. Jang, H.E. Horng, J.M. Wu, Chin-Yih Hong, Y.C. Chiou, H.C. Yang, J. Magn. Magn. Mater. 201 (1999) 317.
- [9] Chin-Yih Hong, Henrg-Er. Horng, F.C. Kuo, S.Y. Yang, H.C. Yang, J.M. Wu, Appl. Phys. Lett. 75 (1999) 5904.
- [10] Chin-Yih Hong, C.H. Ho, H.E. Horng, Chun-Hui Chen, S.Y. Yang, Y.P. Chiu, H.C. Yang, Magn. Gidrodin 35 (1999) 364.
- [11] H.E. Horng, S.Y. Yang, Chun-Hui Chen, Y.P. Chiu, C.A. Chen, Chin-Yih Hong, H.C. Yang, J. Magn. Magn. Mater. 226–230 (2001) 1924.
- [12] Y.H. Ke, S.Y. Yang, H.E. Horng, Chin-Yih Hong, H.C. Yang, E. Phys. D 41 (2004) 319.