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THE OBSERVATION OF VARIOUS STRUCTURES OF MAGNETIC PARTICLES AND MAGNETIC HOLES IN FERROFLUIDS [1)]

НАБЛЮДЕНИЕ РАЗЛИЧНЫХ СТРУКТУР ДЛЯ МАГНИТНЫХ ЧАСТИЦ И МАГНИТНЫХ ДЫРОК В ФЕРРОЖИДКОСТЯХ

KOPČANSKÝ, P.,[2)] VALENČÍK, Ľ.,[2)] TIMA, T.,[2)] ZENTKO, A.,[2)] Košice

Ferrofluids are colloidal dispersions of magnetic particles, ≈ 10 nm in diameter, in a liquid carrier such as an oil, kerosene water and so on. A ferrofluid composite, however, is a dispersion of much larger non-magnetic particles such as polystyrene, copper, tin, approximately 1—10 µm, in the ferrofluid itself. In a magnetic field the nonmagnetic particles appear to acquire a strong induced magnetic moment $\boldsymbol{M}$, which can be written in terms of the effective magnetic fluid susceptibility χ_{eff}. Hence [1]

$$\boldsymbol{M} = -\chi_{eff} \cdot V \cdot \boldsymbol{H}, \tag{1}$$

where V is the particle volume and $\boldsymbol{H}$ is the applied magnetic field. χ_{eff} is equal to the susceptibility of the magnetic fluid to dendritic nonmagnetic particles for example. The nonmagnetic particles in the ferrofluid are denoted as "magnetic holes". The effective dipolar interaction energy between two magnetic holes is simply given as

$$E_{dd} = M^2(1 - 3\cos^3\Theta)/4\pi\mu_0 R^3 \tag{2}$$

for an external field $\boldsymbol{H}$ forming an angle Θ relative to the line of centres of two particles and with the separation R between the particles. μ_0 is the permeability of vacuum.

As it can be seen from eq. (2) the effective dipolar interaction between magnetic holes may be attractive or repulsive when the angle Θ is changed. Therefore, various many-body effects may be visualized including the formation of crystalline lattices, chain and lamellar structures by means of magnetic holes. This offers a wide range of model systems for studies of thermal and structural many-body effects in condensed matter physics [2].

We have studied these effects in a kerosene based ferrofluid with saturation magnetization $I_s = 6.51$ mT and in a ferrofluid composite containing copper particles 1—5 µm in diameter. The mean value of the diameter of magnetic particles $D_v = 12$ nm has been calculated from magnetization measurements using the Chantrell et al. technique [3] for determining the size distribution function. The experimental set up is shown in fig. 1. The thickness of the layer of the ferrofluid or the ferrofluid composite was about 20 µm.

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[2)] Institute of experimental physics, Slov. Acad. Sci., Solovjevova 47, 043 53 KOŠICE, Czechoslovakia

Figure 2 illustrates the chain structure of copper particles when the applied magnetic field was parallel to the plane of observation. The structures observed in fig. 2 bear a close resemblance to particle structures predicted for the magnetic particles in ferrofluids. As a consequence of a dipole-dipole interaction between magnetic particles, a magnetic particle tends to attract the neighbouring magnetic particles in the direction of its magnetic moment. It is expected therefore that the magnetic particles form chain-like clusters in which the particles are connected magnetically. When the magnetic field is absent, the magnetic particles are well dispersed in the liquid carrier. When a weak field is applied, magnetic particles tent to form tiny clusters elongated parallel to the field. A further increase of the magnetic field results in the growth of the clusters, the magnetic interactions between which result in the macroclusters containing many voids. Eq. (1) is now valid but M is the magnetic moment of the cluster of magnetic particles.

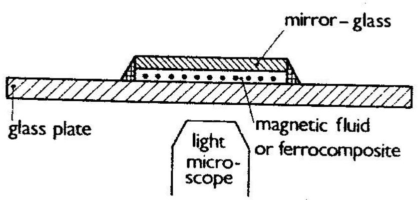

Fig. 1. The experimental set up for the observation of structure configurations in the ferrofluid and the ferrofluid composite.

Fig. 3 illustrates an analogous situation to that in fig. 2, but with the ferrofluid only. When the applied magnetic field is perpendicular to the plane of the observation, we have observed the structure given in fig. 4 (ferrofluid only) and fig. 5 (ferrofluid composite).

Next we have studied the problem of a number of magnetic clusters in a unit area in a ferrofluid as a function of the applied magnetic field in a situation where the magnetic field was perpendicular to the plane of the observation. These observations are shown in fig. 6. It is concluded that there exists a threshold magnetic field B_c for the existence of clusters observed in the light microscope. The threshold magnetic field is indirect proportional to the concentration of magnetic particles. This will be published elsewhere. When the magnetic field is continuously increased, the number of clusters linearly increases with the magnetic field. No hysteresis was observed when the magnetic field was decreased. When the magnetic field was switched on, the value $B > B_c$, the number of the established clusters, was given by the first curve as in the situation when the magnetic field was increased from zero value. But, contrary to the first situation, when the magnetic field was increased, the number of clusters was still equal to the initial value. Only the size of the clusters increased. No hysteresis was observed in this situation either.

A detailed study of clustering requires a complex theoretical investigation of the magnetostatic problem associated with the nucleation and the agglomeration of the clusters. Any lateral growth (an increase of the diameter of clusters) increases the demagnetizing factor and hence the magnetostatic energy. On the other hand the nucleation of clusters is connected with some nucleation energy, for example. A critical point is reached when the accretion to an already existing cluster is less favourable energetically than nucleation. In the first situation (linear dependence of the number of clusters) nucleation more to be expected but in the second situation (constant dependence) the accretion process is more to be expected. The reason is not clear.

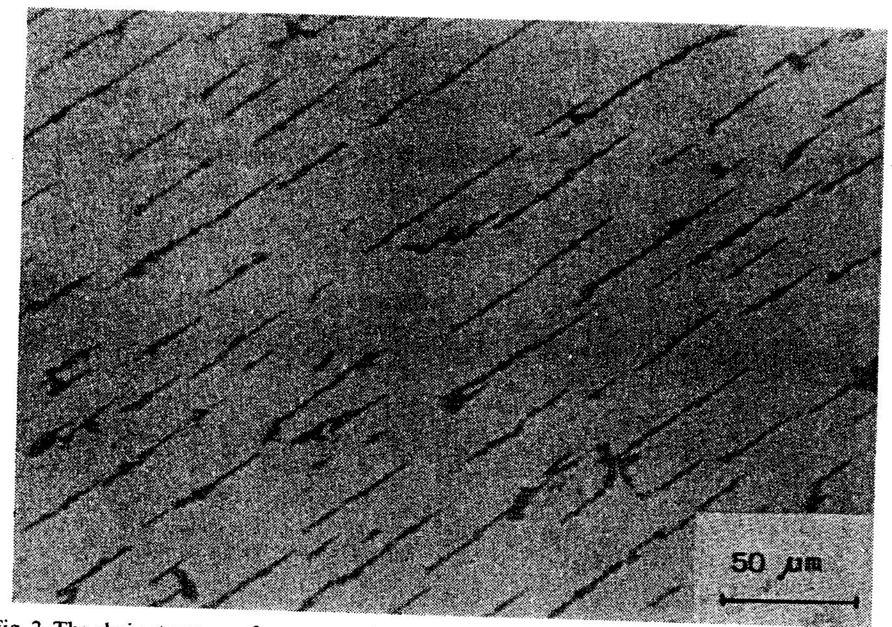

Fig. 2. The chain structure of copper particles when the magnetic field is parallel to the plane of the layer. In all photographs the applied magnetic field was $B = 30\,\text{mT}$.

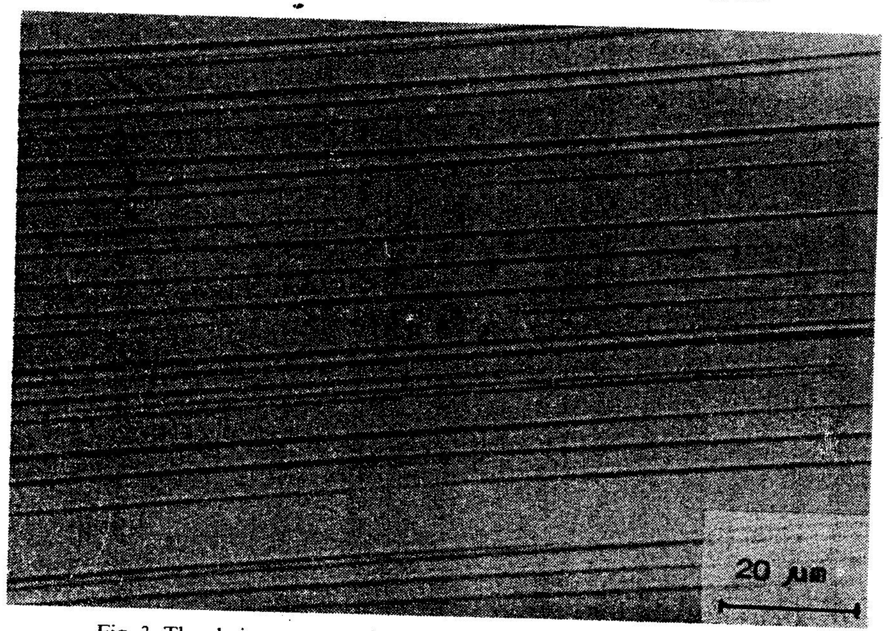

Fig. 3. The chain structure of magnetic particles in ferrofluid only.

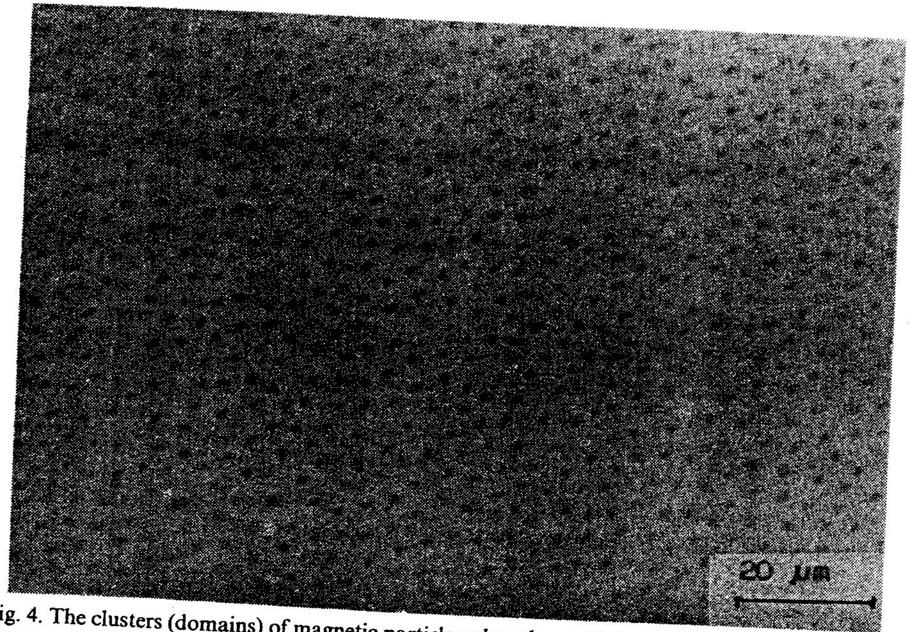

Fig. 4. The clusters (domains) of magnetic particles when the applied magneticfield is perpendicular to the plane of the layer.

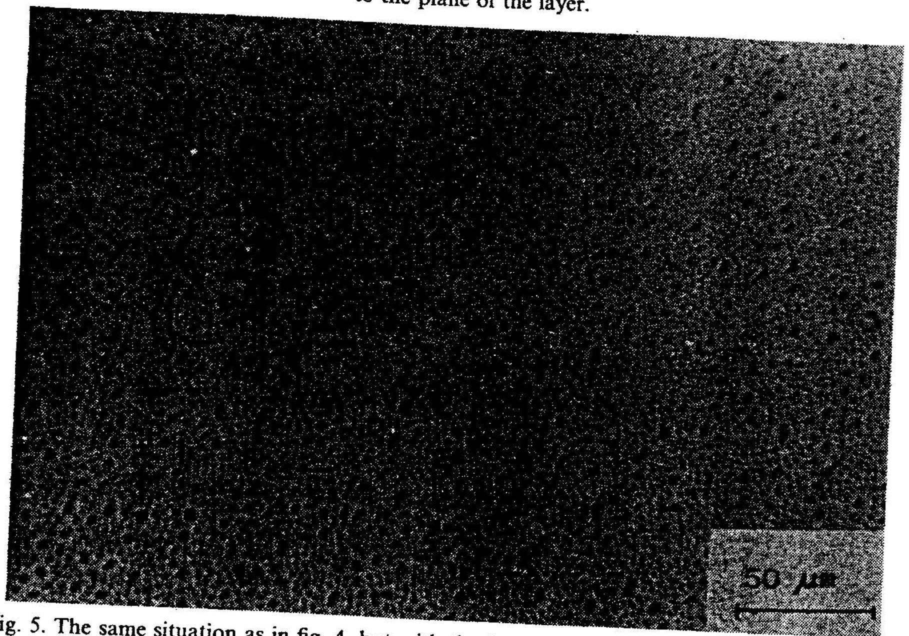

Fig. 5. The same situation as in fig. 4, but with the ferrofluid composite. The larger particles are copper particles.

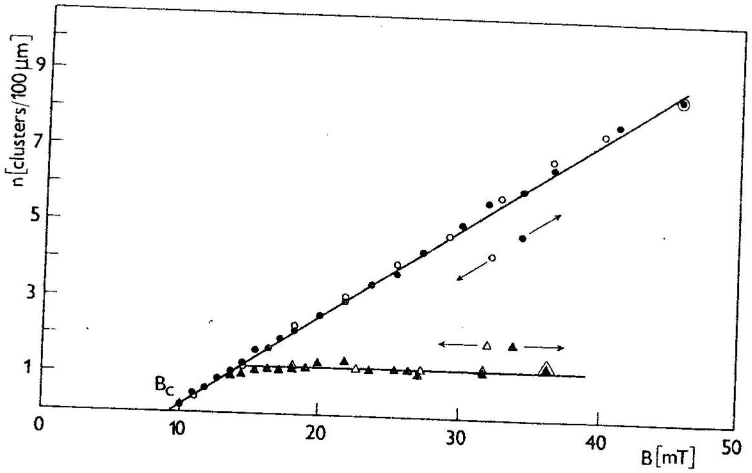

Fig. 6. Number of clusters or domains as a function of the applied magnetic field. B_c is the threshold magnetic field. The full (empty) symbols describe the continuously increasing (decreasing) magnetic field. The constant dependence of the number of clusters was obtained when the magnetic field had been switched on the value $B > B_c$.

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