J. Phys. D: Appl. Phys. **20** (1987) 1540–1541. Printed in the UK

LETTER TO THE EDITOR

Particle size analysis of micrometre-sized particles using magnetic liquids

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Received 11 August 1987

Abstract. A new method of studying non-ferromagnetic particles ($1\ \mu m < d < 60\ \mu m$) using magnetic liquids is discussed. The technique is straightforward and makes particle counting and size analysis simpler and more accurate.

A magnetic liquid (or ferrofluid) is a colloidal suspension of ultra-fine ferro- or ferrimagnetic particles ($d \leqslant 100$ Å) suspended in a carrier fluid. Stability is maintained by coating the magnetic particles with a surfactant of long chain or polymer molecules. The particles are usually ferrites such as Fe_3O_4, the ferromagnetic elements or alloys such as Ni/Fe. Typical carrier liquids are water, diesters or hydrocarbon oils. For a comprehensive review of the properties and preparations of magnetic liquids see Charles and Popplewell (1980).

Skjeltorp (1983, 1985) has shown that if micrometre-sized non-ferromagnetic particles (e.g. monodisperse polystyrene spheres) are added to a magnetic liquid then the non-ferromagnetic inclusions form 'magnetic holes' in the fluid. Upon the application of a magnetic field to the liquid the non-magnetic inclusions acquire an apparent magnetic moment $\boldsymbol{\mu}(H)$ which is given by

$$\boldsymbol{\mu}(H) = \chi_{\mathrm{eff}} V \boldsymbol{H} \tag{1}$$

where $\boldsymbol{H}$ is the applied field, V is the volume of the inclusion and χ_{eff} is the effective fluid susceptibility with demagnetising factors taken into account.

If the sample is in the form of a thin film and the magnetic holes are restricted to a monolayer then the dipolar energy of interaction between two spheres due to their apparent magnetic moment is given to first approximation by

$$E = \mu^2(1 - 3\cos^2\theta)/r^3 \tag{2}$$

where $\mu = |\boldsymbol{\mu}(H)|$, θ is the angle between the field direction and the line joining the centres between the two particles and r is the centre–centre particle separation. It is clear that, depending on the value of θ (i.e. the field orientation), the interaction between spheres can be either attractive or repulsive. If the field is applied perpendicular to the film (i.e. $\theta = \pi/2$) then the interaction energy is given by

$$E = -\mu^2/r^3 \tag{3}$$

and, therefore, the interaction is repulsive; in this case the spheres form a triangular (or hexagonal) lattice. It follows that powders of non-magnetic micrometre-sized particles can be studied in detail by using a magnetic liquid and a magnetic field to disperse the particles.

Figure 1 shows an optical micrograph of copper particles ($d \simeq 38\ \mu m$) immersed in an $M_s = 300$ G ($M_s = 4\pi I_s$) magnetic liquid in zero field. It is clear that some of the particles are not single particles but are

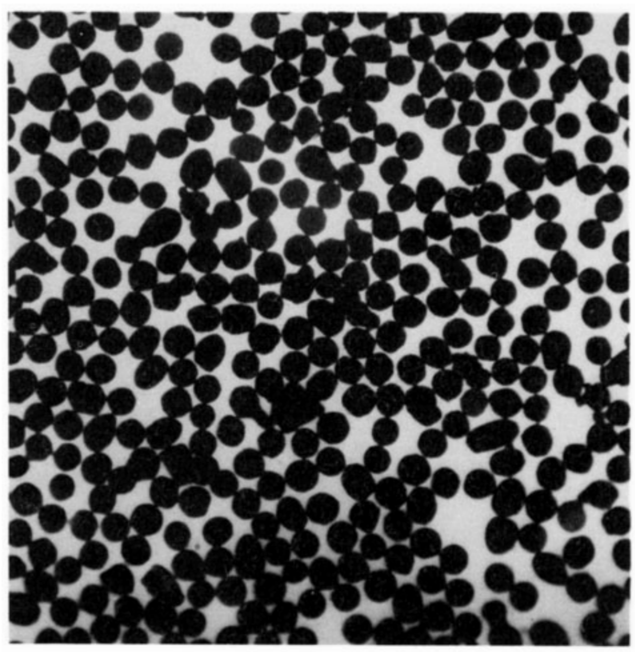

Figure 1. 38 μm copper particles in a magnetic liquid ($H = 0$).

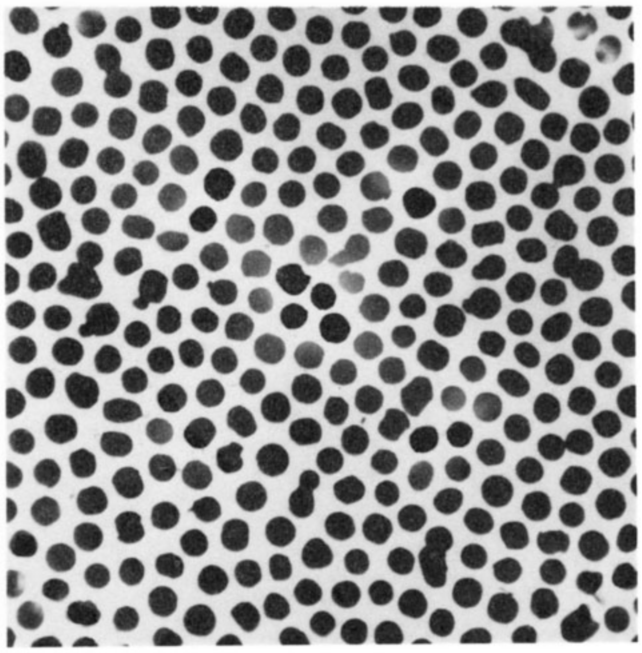

Figure 2. 38 μm copper particles in a magnetic liquid ($H \sim 100$ Oe).

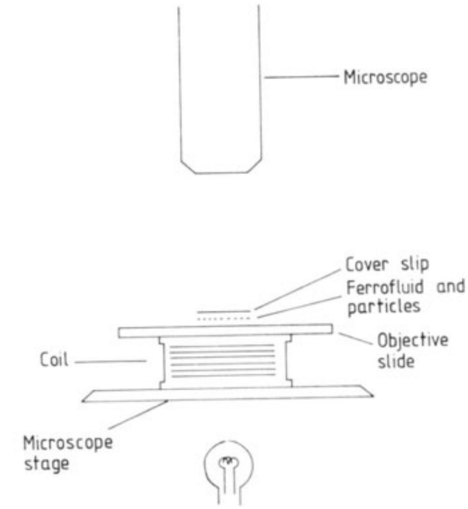

Figure 3. The experimental arrangement.

aggregates made up of two or more particles. This can make quantitative analysis of the number of particles present and the size distribution of the system difficult. However, upon the application of a small magnetic field ($H \leqslant 100$ Oe) the particles form a system of repulsive dipoles. Figure 2 shows that the repulsive force that exists between particles is sufficient to break up the aggregates into discrete particles. The procedure for measuring the size distribution of the particles and their shapes is now much easier and more accurate.

The feature of this method is its simplicity; all that is required is a microscope, a small quantity of magnetic liquid and either a current-carrying coil or a permanent magnet to provide a perpendicular field. A typical experimental set-up is shown in figure 3. The sample is made as follows: a clean microscope slide is taken and a small quantity of the particles to be investigated placed upon it. Using a pippette the particles are covered with 2–3 drops of ferrofluid and then a cover slip. By pressing down on the cover slip excess liquid is expelled and a monolayer of particles is obtained. It also helps if the cover slip is moved in a circular motion to dislodge any particles which may have become attached to the objective slide. The slide is now ready for investigation and can be placed on the ring magnet or coil. A typical coil which will produce a field of approximately 100 Oe has an external diameter of 7 cm, an internal diameter of 5 cm and a depth of 1.5 cm. If the coil is now wound with approximately 800 turns of 0.2 mm diameter wire and is driven by a direct current of ~3–400 mA then a field of ~100 Oe will result.

One consideration must be taken into account; magnetic fluids are optically dense materials. Thus this method can only be used for particles with diameters of $\leqslant 60$ μm. Also a high-intensity bulb in the microscope is advised and a ferrofluid with $250\ \mathrm{G} \leqslant M_s \leqslant 350\ \mathrm{G}$ used.

Figure 2 shows the clarity with which particles can be studied using the ferrofluid technique described. Individual particle shapes and sizes are readily apparent and can be studied with ease. In the case of the copper particles shown the regularity of size and shape is noticeable and the particles studied (obtained from Fluoridienne Ltd, UK) are unlike most commercial powders. Clearly, this technique is even more useful for studying irregularly shaped, polydisperse particle systems.

The technique of using magnetic liquids for characterisation of polydisperse systems of micrometre-sized particles could be useful in areas of study outside physics such as soil science and the life sciences.

References

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