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"P" curves for micro-structural characterization of magnetic suspensions

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Abstract

The paper defines, describes, and presents the "P" curves for micro-structural characterization of the complex fluids, complex powders, and complex solid matrix, having magnetic properties. P curves are the first derivative (relative to the magnetic field strength) of the hysteresis curves relative to the saturation magnetization. They offer the possibility to investigate live biological materials without sample extraction.

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Keywords: P curves; Magnetic fluids; Ferrofluids; Micro-structural characterization; Magnetic powders; Hysteresis curve

1. Introduction

In the lasts years, many types of complex fluids having magnetic properties were artificial prepared [1–5]. These magnetic properties are conferred to various carrier liquids (water, alcohol, oil, etc.) by integrating in their structure ferromagnetic particles of different sizes. Depending on the dimensions of the ferromagnetic particles from their structure these complex fluids runs between magnetic fluids (ferrofluids) and magneto-rheological suspensions (or others complex fluids obtained from these).

In the case of magnetic fluids, the ferromagnetic particles are usually magnetic ferrite of 10 nm in diameter and being chemically covered with a surfactant layer [6]. This layer (together with thermal agitation) ensures the colloid stability, so that the entire fluid is quasi-homogeneous and has an excellent macro-stability in gravitational and/or magnetic field. The ferrofluids present very small magneto-rheological effect.

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In the case of magneto-rheological fluids, the ferromagnetic particles are usually iron made having the diameters of a few micrometers [7].

For the biological or technical applications [8,9] of these complex fluids, the magnetic properties and the micro-structural characteristics of the fluids must be known. The magnetic properties are usually shown by the hysteresis curve (macroscopic measurements). The structure can be seen on the (electronic) micrography of the fluids.

The paper defines and describes the "P" (peak) curves for micro-structural characterization of the complex fluids (or complex powders) having magnetic properties. The "P" curves offer a possibility to know the microstructure (or a modification of micro-structure) of the magnetic component of a complex fluid (or complex powder) by numerical derivation of the magnetization curve experimentally obtained. The experimental measurements were performed using a vibrating sample magnetometer (VSM 880—ADE Technologies/USA) on some types of magnetic suspensions and ferrofluids. The advantages of the P curves are presented in the discussion.

2. P curves in magnetic suspensions

Fig. 1 presents the hysteresis curves for three different magnetic suspensions, characterized using their volume magnetization M versus magnetic field strength H. (In the next investigations the carrier liquids are not relevant so we do not refer to them.)

Generally speaking, on the hysteresis curves, we can see mainly the saturation magnetizations and we can determine the magnetic permeability in different points. (As it is known, ferrofluids and magnetic suspensions do not have hysteresis loop.) These two physical parameters are very important for the dimensioning of some applications [9] and strongly depend on the ferromagnetic fraction of the suspension. (The three suspensions from the above have different ferromagnetic fractions.)

It is possible to obtain some information about the micro-structure of the suspensions using the hysteresis curves relative to the saturation magnetization (Fig. 2) or their first derivative relative to the magnetic field strength H. So, we define the P_X value (in m/kA) of the hysteresis curve in the point X (having coordinates H_X and M_X):

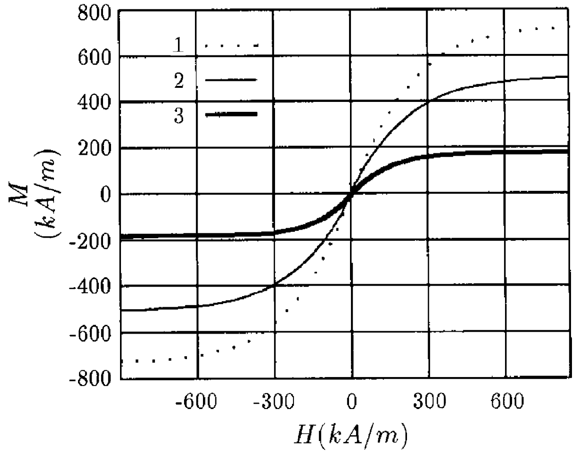

Fig. 1. Hysteresis curves for three different magnetic suspensions. The saturation magnetizations are $M_{s_1} = 723$ kA/m, $M_{s_2} = 504$ kA/m, and $M_{s_3} = 180$ kA/m.

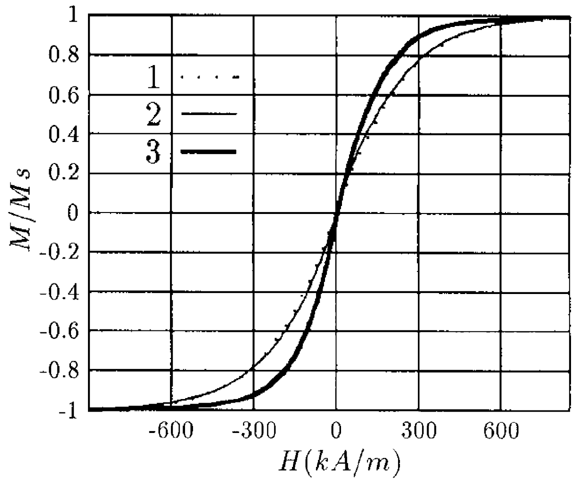

Fig. 2. Hysteresis curves from Fig. 1 relative to their saturation magnetization M_s.

$$P_X = \frac{\mathrm{d}(M_X/M_s)}{\mathrm{d}H_X}. \quad (1)$$

Fig. 3 presents the P curves for the three magnetic suspensions from Figs. 1 and 2.

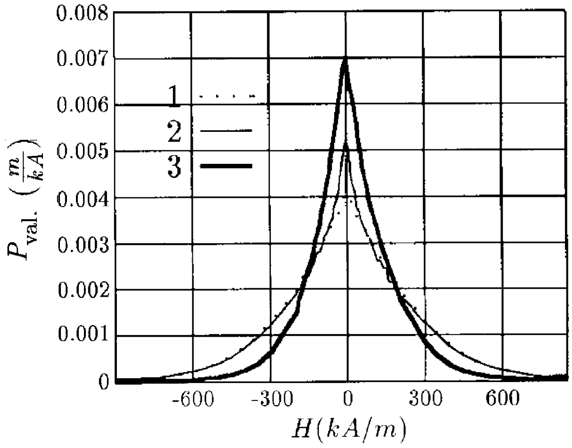

Fig. 3. P curves for the three different magnetic suspensions from Figs. 1 and 2.

The diameter of the magnetic iron particles was about 25 (M_{s_1}, Hoeganaes Europe, Romania), 15 (M_{s_2}, [10]), and 4 μm (M_{s_3}, [7]).

3. P curves in ferrofluids

Fig. 4 presents the hysteresis curves for three different ferrofluids. The P curves of these ferrofluids are shown on Figs. 5 and 6.

The diameter of the magnetic particles was about 10.5 nm (M_{s_4}, ferrite, [6]), 8.5 nm (M_{s_5}, ferrite, Ferrofluidics, USA), and less than 5 nm (M_{s_6}, Fe-C, [11]).

From Figs. 3, 5 and 6 we can observe that the height of the P curves is greater when the magnetic particles are smaller, and, the spread of the P curves is wider when the magnetic particles are of greater dimensions. So, we can define at least an important parameter, the amplitude of the P curves in the point $H = 0$, P(0).

4. P curves in solid matrix

We investigated some magnetic suspensions and ferrofluids, embedded in a solid matrix. We placed the magnetic particles (from suspensions or ferrofluids) in a fluid material having the ability to

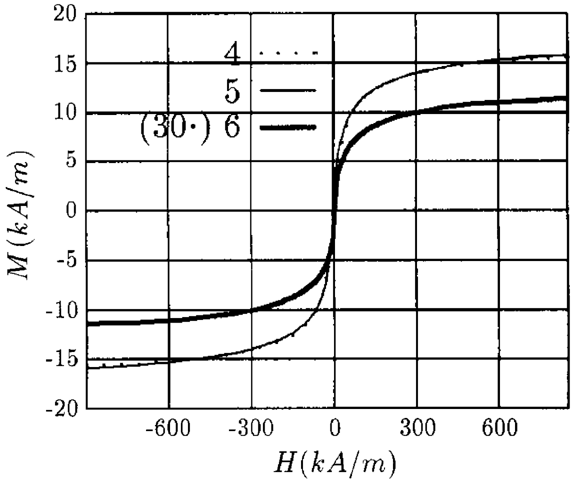

Fig. 4. Hysteresis curves for three different ferrofluids. The saturation magnetizations are $M_{s_4} = 15.6$ kA/m, $M_{s_5} = 15.9$ kA/m, and $M_{s_6} = 0.38$ kA/m. For visibility M_6 was multiplied by a factor of 30.

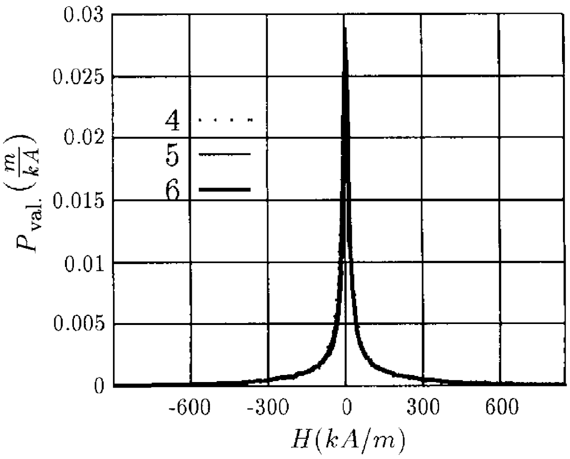

Fig. 5. P curves for the ferrofluids from Fig. 4. For details see Fig. 6.

solidify in a few hours. This solidification was made in a magnetic field, stronger than the saturation magnetic field of the magnetic particles.

Fig. 7 presents the P curves for the solid matrix containing Fe particles (about 3 μm) from a magnetic suspension. In Fig. 7, we determined the P curves with the measurement of magnetic

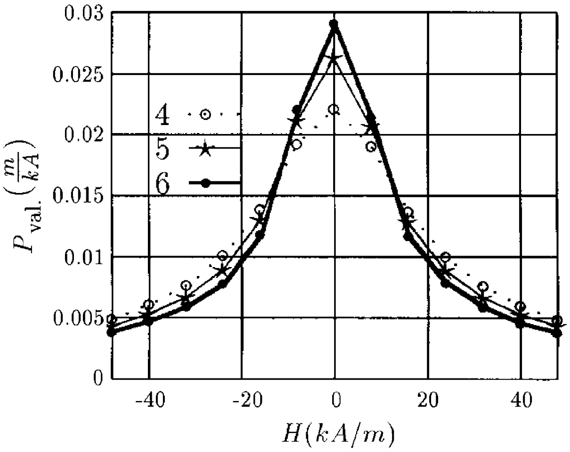

Fig. 6. Detail of Fig. 5.

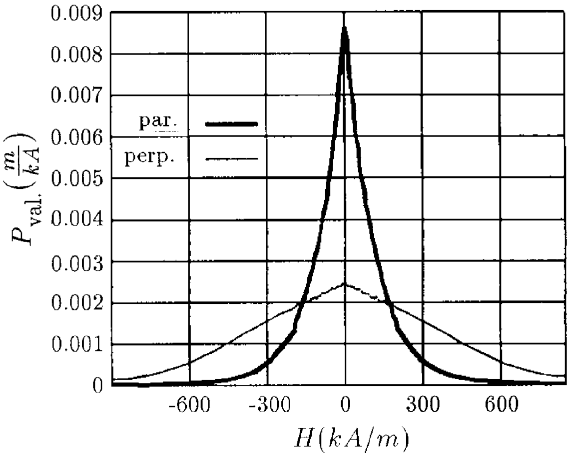

Fig. 7. P curves for magnetic suspension in solid matrix. The matrix solidification was made in a magnetic field parallel (par.) or perpendicular (perp.), respectively, to the measurement magnetic field.

field parallel and perpendicular to the solidification magnetic field.

On the same way, Figs. 8 and 9 presents the P curves for a solid matrix containing ferrite particles (about 10 nm) from a ferrofluid.

The P curves for the solid matrix having the same magnetic particles but solidified outside the magnetic field are between the "par." and "perp." curves.

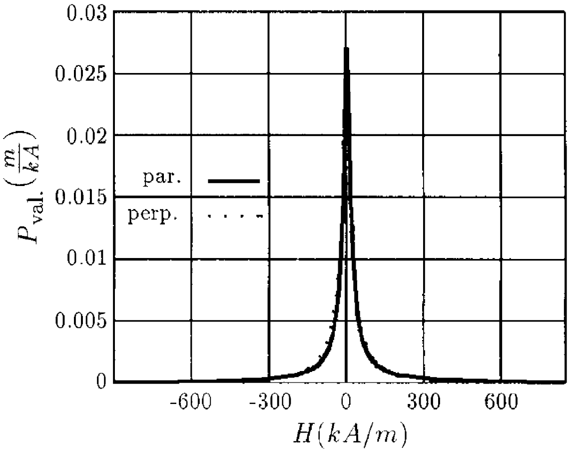

Fig. 8. P curves for ferrofluids in solid matrix. For details see Fig. 9.

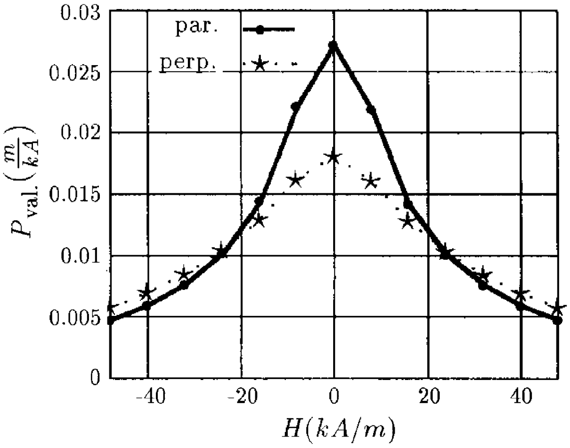

Fig. 9. Detail of Fig. 8.

From the Figs. 7, 8 and 9, for P curves in solid matrix we can define the "P Shape Factor":

$$\mathrm{PSF} = \frac{P(0)_{\mathrm{par}}}{P(0)_{\mathrm{perp}}}. \tag{2}$$

5. Discussion

The P curves for micro- and nano-magnetic suspensions may be considered also for $H \geqslant 0$ or for $H \leqslant 0$ only. We used the both values of H to observe the hysteresis loops for great dimension ferromagnetic particles. We concluded that these loops are not relevant for our investigation.

There are some advantages of the P curves, which encourage their use.

1. With a previous calibration (of P curves) using spherical particles (for every magnetic material or combinations) we can obtain information concerning the presence, dimension, modification or orientation (see PSF) of the magnetic particles. So, the P value is related to the microstructure through a previous calibration.

2. The P values are the same if we use the volume magnetization or the mass magnetization.

3. The P values do not depend on the accuracy of the magnetometer y-axis calibration.

4. The P values do not depend on the accuracy of sample mass or volume measurement.

5. The P values do not depend on the accuracy of the saturation magnetization (M_s) measurement (the others values of magnetization M are proportional to M_s). In fact, a vibrating sample magnetometer works with the magnetic polarization. The volume or mass magnetization results from magnetic polarization, making some calculations. The P curve can be determined directly from magnetic polarization. We used the hysteresis curve because it is more usual.

6. From the advantages 2–5, we get the most interesting application for P curves. It is possible to investigate (from the magnetic point of view) the living biological material, without extracting a sample. It is possible to place a branch of a plant between the poles of magnetometer, and, by gently vibrating this branch it is possible to extract the P curves. For medical applications, construction of magnetometers with vibrating poles (and pick-up coils) cannot be neglected.

P curves also exist for massive ferromagnetic materials. Fig. 10 presents the P curve for a massive sample of nickel (the measured coercive field is 3.05 kA/m). This P curve leads to the magnetic microstructure of massive materials (Weiss domains). If the physical dimensions of the sample decrease, when the dimensions of ferromagnetic material (particle) are not extremely far from the Weiss domain dimensions, the P curve starts to change its aspect (measurable). The P curve continues this transformation when the particles reduce their dimensions under Weiss domain dimensions. It seems that the superior application limit for P curves in magnetic suspensions is for the particles with diameters of 20 μm.

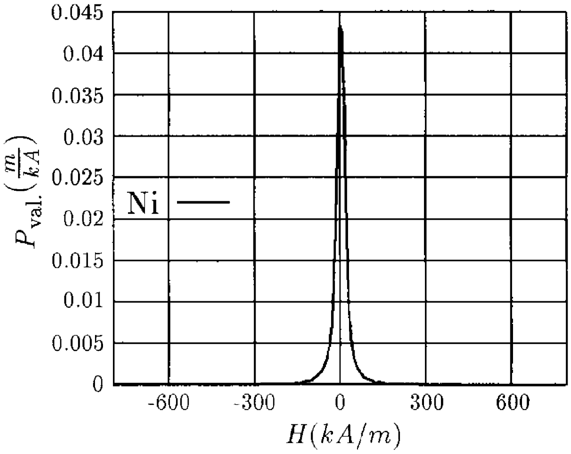

Fig. 10. P curves for massive ferromagnetic material (Ni).

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