Features of Magnetization of Ferromagnetic Composites: Role of Grain Chains on an Example of Granulated Media

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An original approach to measuring magnetic (micro) fluxes along cores of different radii in a magnetized chain of ferromagnetic spheres has been developed and described. It is based on the use of radially different circular circuit sensors created using the technology of printed circuit boards and placed between contacting spheres in a chain. Such stepwise magnetic flux data also made it possible to judge the data of stepwise changes in magnetic flux in conventional tubular layers (limited by adjacent circular sensors). Based on all these data, extensive information was obtained on the magnetic parameters of the cores and "pipe-layers" of the magnetized chain of spheres (as quasi-continuous ferromagnets), namely, the values of flux density (induction) in the cores and "pipe-layers", their magnetic permeability, susceptibility, magnetization in a wide range of magnetizing field intensity. The purpose of the article is to develop a model of chain-by-chain magnetization of granular media, in which chains of granules are basic elements.

Keywords: Magnetic Permeability, Magnetic Flux, Granulated Medium, Grain Chains.

Introduction

The magnetic properties of different heterogeneous mediums, including ferro and ferrimagnetic composites, for example, granular mediums, are usually studied from the standpoint of the model of the so-called effective medium when it is formally likened to quasi-continuous (throughout the volume) [1-9]. In relation to such heterogeneous (discrete) mediums as filling of ferromagnetic granules (used to solve scientific and practical problems), the physical model of their chain-by-chain magnetization is additionally informative [6, 10, 11]. According to this model, the chains of granules that carry information about the magnetic properties of the granular medium as a whole, in connection with which a detailed study of their magnetic properties is of independent interest.

Direct measurements of magnetic fluxes (by webermeter) Φ_c were carried out along loops made of thin wire of different radius $r_c < R$, that were located in the plane of symmetry of the hollow volume between the chain'spheres (used in [6, 10, 11]). Thus, the values of Φ_c were determined in the corresponding cores' radius r_c of the chain' spheres. By deepening the sensor loops into the volume between spheres, it was possible to obtain Φ_c values in the cores of even a relatively small relative radius r/R: for this, chains with spheres of increased radius and loops with very thin wire were used. Loops was placed as deep as possible in the thinning (when approaching the spheres' contact point) volume between the surfaces of the spheres.

It was shown in [12, 13], that a sensor in the form of a thin printed circuit board with a conductive circular circuit or a concentric circuit block is preferable for measuring Φ_c. With this approach, which increases the reliability and quality of the abovementioned magnetic measurements, it is easy to ensure the required strict shape of the circle on the flat surface of each of the sensor circuits and their concentric relationship to the contact point of the spheres and to each other. It is also easy to ensure the verified positioning of this working board *1* (Fig. 1) in the plane of symmetry of the volume between the contact spheres *2* with radius *R*. This is served by a mounting bore in the centre of working board that concentric to contour-sensor or block of contours-sensors. The diameter of bore should comply with the recommendation [12, 13], based on the radius *R* of spheres and depth of the board.

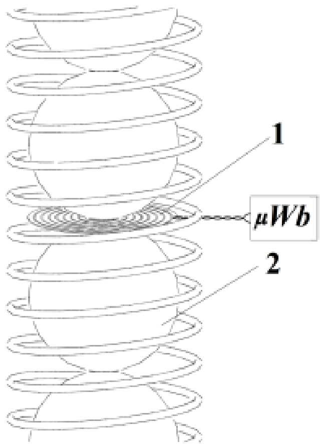


Figure 1: A chain of spheres 2 (located in solenoid) with a circular loop-sensor 1 connected to the microwebermeter.

Results and Discussion

The values of the magnetic microflux Φ_c through the sensor circuits [12, 14] were measured, and therefore through the cores corresponding to the radius r_c by the use of a chain of spheres with a radius of R = 15 mm, as well as an additional chain of spheres with a radius of

R = 20 mm. The data were obtained using a sufficiently long chain of spheres (with the number of spheres in the chain of at least 10 - for the minimization of the demagnetizing factor), the range of change in the intensity of the magnetizing field H = 5-55kA/m, and the range of change in the relative radius of the cores: r_c/R = 0.2-0.9. Based on experimental data Φ_c it is not difficult to obtain data of magnetic induction B_c in each of quasi-continuous cores with radius r_c and cross-section equals πr_c^2, as:

$$B_c = \frac{\Phi_c}{\pi r_c^2}, \tag{1}$$

and magnetic permeability μc data of corresponding cores, as

$$\mu_c = \frac{B_c}{\mu_0 H} = \frac{\Phi_c}{\pi r_c^2 \mu_0 H}, \tag{2}$$

where μ_0= 4π·10^{-7} H/m – magnetic constant.

The data of B_c and μ_c in the form of families of H-dependencies of B_c and μ_c for different (by r_c/R) cores are shown in Fig. 2. As the field intensity H increases the induction B_c in each core increases (Fig. 2a) and the permeability of the cores decreases (Fig. 2b). Thy larger the core radius r_c the smaller the B_c and μ_c (Fig. 2). In addition, as can be seen from the data of B_c (and the μ_c data, Fig. 2) obtained for a chain of spheres with a radius of R = 15 mm (shaded points) and a chain of spheres with a radius of R = 20 mm (not shaded points), they are mutually matched. This makes it possible to judge the obtained result as having a certain versatility, i.e. fair for chains of spheres of a particular radius.

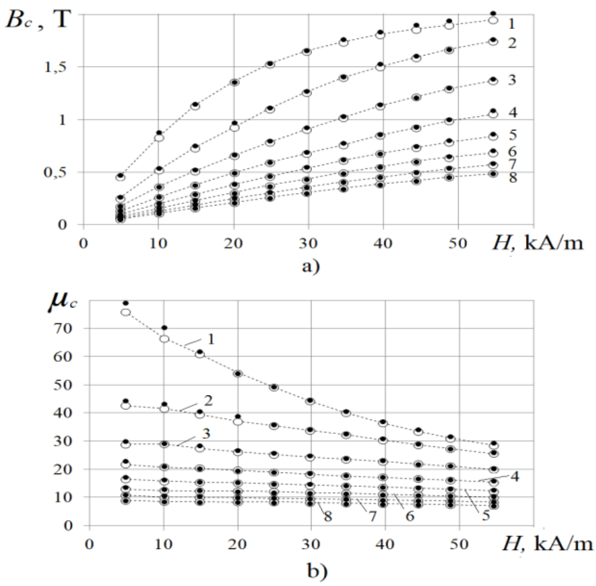


Figure 2: Magnetic induction B_c data (a) and magnetic permeability μ_c (b) for different (r_c/R) cores of chain of spheres in the dependence from intensity of the magnetizing field H: *1* –

r_c/R=0.2; *2* – 0.3; *3* – 0.4; *4* – 0.5; *5* – 0.6; *6* – 0.7; *7* – 0.8; *8* – 0.9. Shaded (•) and not shaded (○) points belong to chain of spheres with a radius R = 15 mm and R = 20 mm accordingly.

The observed in Fig. 2 decrease in B_c and μ_c values as the radius r_c of conditional cores increases (the relative radius r_c/R can vary from $r_c/R \to 0$ to $r_c/R = 1$) is due to a decrease in the volume fraction of ferromagnetic metal in the thickening core.

Using the data in Figure 2a, it is possible to obtain field dependencies of magnetic induction $B_c = B$ and permeability $\mu_c = \mu$ for the chain as a whole ($r_c/R \to 1$), although in the experiments in Figure 2 the largest relative radius of the sensor circuits (and the conditional cores of the spheres covered by them) was limited to $r_c/R = 0.9$. Thus, the trends in the r_c/R-dependencies of B_c and μ_c are amenable to quite objective extrapolation to $r_c/R = 1$, the more so because at $r_c/R = 0.9$ the differences in the values of both the values of B_c and μ_c from $B_c = B$ and $\mu_c = \mu$ indicated by such extrapolation are very insignificant (Fig. 2).

The field dependences of induction $B_c = B$ and permeability $\mu_c = \mu$ for the chain (at r_c/R = 0.9-1) are shown in Fig. 3 (curves *1*). Available at [6] the field dependencies B and μ for media of polyball filling also illustrated here, Fig. 3 (curves *2*). It can be seen that the comparable field dependences of both induction B (Fig.3a, curves *1* and *2*) and permeability μ_c (Fig.3b, curves 1 and 2) are traceable to each other. Thus, it is confirmed that the chain of granules is a physically self-sufficient element (as part of a "bundle" of similar elements) of the granular medium, which is immediately responsible for magnetizing this medium.

Based on the data of magnetic fluxes Φ_c in eight conditional cores of spheres with relative radius r_c/R (from 0.2 to 0.9), it is possible to obtain data on magnetic flux Φ_p in seven thin "pipe-layers" as $\Phi_p = (\Phi_c)_{i+1} - (\Phi_c)_i$, where $(\Phi_c)_{i+1}$ and $(\Phi_c)_i$ are magnetic fluxes, respectively in (i + 1)-th core of larger radius and adjacent i-th core of smaller radius. Note here that relative radii of r_p/R possible here for study of "pipe-layers" represent average values between relative radii of i-th and (i + 1)-th cores, respectively; values of the relative radius of the "pipe" layers r_p/R here ranged from 0.25 to 0.85.

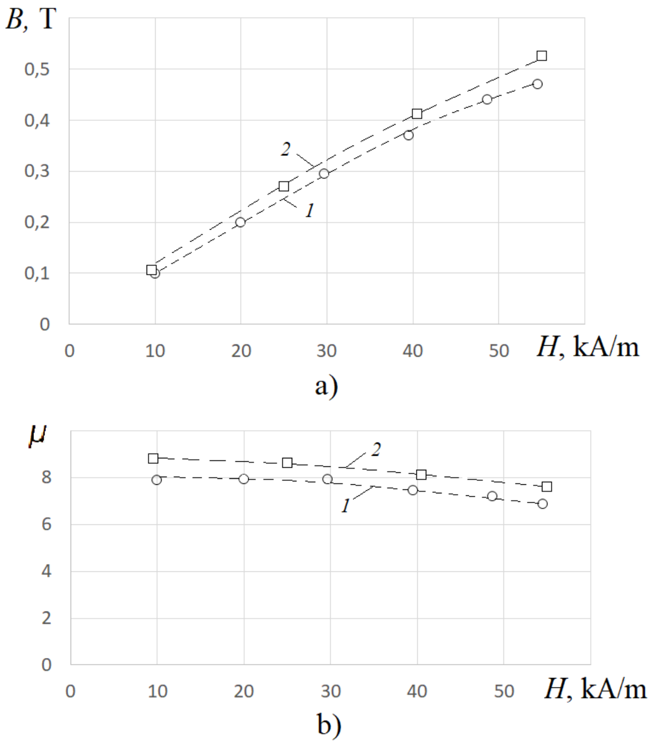
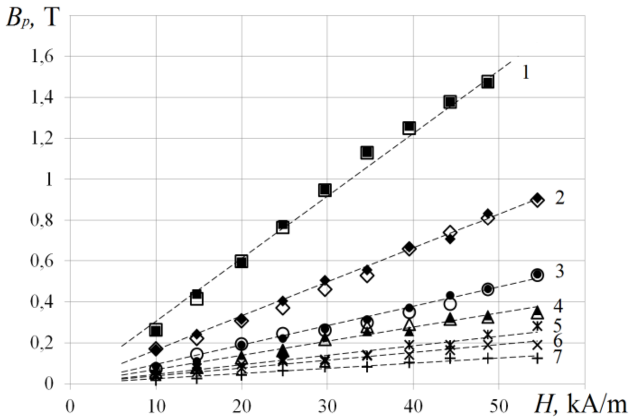


Figure 3: Field dependencies of magnetic induction B (a) and magnetic permeability μ (b): *1* – for chain of spheres (at r_c/R =0.9-1); *2* – for polyball media.

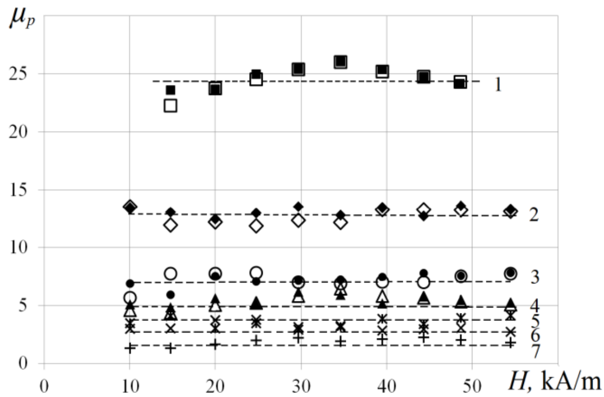
It has been found that the empirically obtained field dependencies of Φ_p can be approximated by linear (direct proportional) dependencies in the studied intensity range of the magnetizing field H. If proceed from the magnetic flux data Φ_p in the pipe "layers" to the corresponding data of its density, i.e. to the magnetic induction data B_p (taking into account the cross-sectional area of a particular layer), using the obvious connection here:

$$B_p = \frac{\Phi_p}{\pi(r_c)^2_{i+1} - \pi(r_c)^2_i}, \tag{3}$$

then the field dependencies of B_p in the corresponding pipe "layers" (Fig. 4a), typically, also become very close to linear. But such linearization is associated with a noticeable error for a pipe "layer" of comparatively inconsiderable relative radius (at r_p/R = 0.25 and obviously at $r_p/R \leq 0.25$).



a)



b)

Figure 4: Magnetic induction B_p data (a) and magnetic permeability μ_p (b) for different relative radius of pipe "layer" of chain in the dependence from intensity of the magnetizing field H: *1* – r_p/R = 0,25; 2 – 0,35; 3 – 0,45; 4 – 0,55; 5 – 0,65; 6 – 0,75; 7 – 0,85. Shaded (■, ♦, ●, ▲) and not shaded (□, ◊, ○, Δ) points of dependences 1-4 belong to chain of spheres with a radius R = 15 mm and R = 20 mm accordingly; points (⁎, ×, +) of dependences 5-7 are common for R = 15 mm and R = 20 mm.

The observed type of H-dependencies of B_p (Fig. 4a) is close to linear and also indicates that in the accepted range of magnetizing field intensity H the magnetic permeability μ_p for each of the studied pipe "layers" is calculated as:

$$\mu_p = \frac{B_p}{\mu_0 H} . \qquad (4)$$

and is close to a constant, individual value for a specific r_p/R pipe "layer" (Fig. 4b). Anyway, this is true for pipe "layers" with a relative radius of r_p/R = 0.35 or more; it is possible to said about the constancy of the μ_p (in the received range of H) for a pipe "layer" with r_p/R = 0.25

(and less) focusing on the average value of μ_p.

As for the influence of the relative radius r_p/R on their magnetic permeability μ_p of the studied "layers" (Fig. 4b), it decreases with an increase in r_p/R.

From the comparison of the data B_p and μ_p obtained for the "pipe-layers" of these chains, it can be seen that the data B_p, like the data μ_p, are traceable to each other, as before, when comparing the specific data of the B_c, μ_c (Fig. 2) obtained for the core of a chain of spheres with a radius of R = 15 mm and the r_c/R-like chain of spheres with a radius of R = 20 mm. This reinforces the earlier judgment that the results obtained by magnetic diagnostics using spheres of any radius have a certain versatility (in this case, when it becomes possible to expand the scope of experiments), i.e. results are valid for chains of a particular radius.

Note that the values of the magnetic permeability of pipe "layers" μ_p seem to be axially important not only in terms of obtaining information about one of the basic physical parameters (in this case, the magnetic permeability of such a specific magnetic as a quasi-continuous pipe "layer" in a chain of spheres). This parameter, moreover, also shows how many times the intensity of the field h in the space between the spheres (locally: at a distance r_c from the axis of a particular "layer") exceeds the intensity of the magnetizing (chain) field H [6, 11, 15, 16]. Thus, the value of magnetic flux in a thin quasi-continuous "layer" with a cross section s_p can be written in the form: $\Phi_p = \mu_0\mu_p \cdot H \cdot s_p$. At the same time, for the real section of the "layer" precisely in the space between the spheres: $\Phi_p = \mu_0 h \cdot s_p$. It really follows from the comparison of these expressions that [6, 11, 15, 16]:

$$\mu_p = \frac{h}{H}\,. \tag{5}$$

Thus, obtaining data on the magnetic permeability of a pipe "layer" in a quasi-continuous chain of spheres is of significant scientific and practical interest, when the goal of diagnostics a field in a hard-to-reach narrow space between spheres is also pursued. According to Fig. 4b and expression (5), it is possible to quantify this value of exceeding the intensity of the field h between the spheres compared to the intensity H of the magnetizing (chain of spheres) field. So, the value of h exceeds the value of H by an order of magnitude or more at a distance less than r_p/R = 0.4from the point of contact of the spheres, which makes it possible to qualify this fact as a hyper-amplification of the field. And even at r_p/R > 0.4 up to r_p/R = 0.85, i.e. almost on the periphery of the region between spheres, the h-value exceeds the H-value for several times.

The obtained data make it possible to use them, in particular, for solving problems of fine magnetic separation (filtration by using magnetizable media-matrices) of mediums, when there is a need for information about actual values of field intensity directly in the magnetic separation zone.

Conclusions

In order to find out the magnetic parameters of the conventional cores of the chain of granules, as a physically self-sufficient element of the granular medium (in accordance with the model of chain-by-chain magnetization of such a medium), it is advisable to make measuring magnetic flux sensors in the core in the form of circular circuits on thin printed circuit boards placed between adjacent contacting spheres. Based on the obtained magnetic flux data in r_c-different cores (eight, r_c/R = 0.2 to r_c/R = 0.9) chains of spheres with radius R = 15 mm and another with radius R = 20 mm values of magnetic induction B_c in them, as well as magnetic permeability μ_c are determined by magnetizing chain in the solenoid with field intensity from 5 to 55 kA/m. As the cores are thickening the B_c and μ_c values decrease due to a decrease in the volume of the ferromagnetic in the core, and for the limit core ($r_c/R \rightarrow 1$), that is, for the chain as a whole, they correspond to the values of magnetic induction and magnetic permeability for the polyball filling media. Thus, it is confirmed that the chains of granules are responsible for magnetizing the granular media.

Experimental data of magnetic fluxes obtained using assumed cores of magnetized chain of spheres made it possible to establish data of magnetic fluxes on "pipe-layers" of average radius r_p/R: from 0.25 to 0.85. Field dependencies of magnetic induction B_p in each of the pipe "layers" showed that they are close to linear in the accepted H-range. Thereby here values of their magnetic permeability are almost constant, individual for different "layers", μ_p which is also the carrier of important information on that how much local intensity of field between spheres h exceeds H-values.

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References

[1] Périgo E. A., Weidenfeller B., Kollár P., Füzer J. (2018) Past, present, and future of soft magnetic composites. Appl Phys Rev. 5:031301.

[2] Strečková M., Füzer J., Kobera L., et al. (2014) A comprehensive study of soft magnetic materials based on FeSi spheres and polymeric resin modified by silica nanorods. Mat Chem Phys. 147:649-660.

[3] Kanhe N. S., Kumar A., Yusuf S. M., et al. (2016) Investigation of structural and magnetic properties of thermal plasma-synthesized Fe1− xNiχ alloy nanoparticles. J Alloys and Compounds. 663:30-40.

[4] Yurasov A. N., Yashin M. M. (2020) Accounting for the influence of granule size distribution in nanocomposites. Rus Techn J 2:59–66

[5] Kollár P., Birčáková Z., Vojtek V., et al. (2015) Reversible and irreversible DC magnetization processes in the frame of magnetic, thermal and electrical properties of Fe-based composite materials. J Magn Magn Mat. 388:76-81.

[6] Sandulyak A.V. (1988) Magnetic and filtration purification of liquids and gases. Chemistry, Moscow. https://dlib.rsl.ru/viewer/01001440011#?page=136]

[7] Bai K., Casara J., Nair-Kanneganti A., Wahl A., Carle F., Brown E. (2018) Effective magnetic susceptibility of suspensions of ferromagnetic particles. J Appl Phys. 124:123901.

[8] Moore R. L. (2019). Development of a volume fraction scaling function for demagnetization factors in effective media theories of magnetic composites. .AIP Advances. 9:035107.

[9] Moore R. L. (2019) Development and test of concentration scaled demagnetization in effective media theories of magnetic composites. J Appl Phys. 125:085101.

[10] Sandulyak A. A., Sandulyak D. A., Ershova V. A., Sandulyak A. V. (2017) Analysis and Modelling of Advanced Structures and Smart Systems. 81:191–210.

[11] Sandulyak A. V., Sandulyak A. A., Ershova V. A. (2009) On the model of channel-by-channel magnetization of a granular medium (with a radial permeability profile of a quasi-continuous

channel). Technical Physics. 54 (5):743–745.

[12] Sandulyak A. V., Gorpinenko Y. O., Polismakova M. N., Sandulyak D. A., Sandulyak A. A. (2020) Magnetic flow and induction in the hearts of magnetizable ball chains. Int Res J. 6 (96):96-110.

[13] Sandulyak A. A., Sandulyak D. A., Gorpinenko Y. O., Sandulyak A. V., Ershova V. A. (2022) A chain of granules as a model element of a "bundle" of chains in a magnetized matrix: New opportunities for diagnostics. J Magn Magn Mat. 546:168911.

[14] Sandulyak A. A., Sandulyak D. A., Gorpinenko Y. O., Sandulyak A. V., Ershova V.A. (2022) An Approach to Monitoring of Magnetic Parameters of Cores of a Chain of Spheres. Diagnostics of Different Chain's Length and Core's Radius. Dev Meth Measurements. 13 (2):117–127.

[15] Sandulyak A. A., Sandulyak A. V., Shitikova M. V., Tkachenko R. Yu., Sandulyak D. A., Gorpinenko Y. O. (2021) Concentrated dispersed magnet with different relative lengths: Basic properties and characteristics (on the example of a polyspherical structure). Mechanics of Advanced Materials and Structures, DOI: 10.1080/15376494.2021.1943575

[16] Sandulyak A. V., Sandulyak A. A., Ershova V. A. (2007) Magnetization curve of a granulated medium in terms of the channel-by-channel magnetization model (new approach). Doklady Physics. 52 (4):179–181.