Characteristics of magnetic parameters of granular samples with various relative length

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Abstract. The experimental data of magnetic flux and induction in ferromagnetic granular samples (filling of balls with 8mm diameter in a cylindrical container with diameter \( D = 40\)mm) have been obtained with various relative lengths of samples \( L/D = 1−16 \) in a magnetizing field with strength range \( H = 9.4−47.2\)kA/m. These data have been used to determine the corresponding dependencies families of magnetic permeability, susceptibility, and magnetization, as well as the demagnetizing factor data of such samples. The absence of magnetic saturation of granular (as opposed to solid) magnetics in the considered range \( H \) has been revealed (by analyzing the trend of induction field dependencies and especially magnetization). From the experiment, it is evident that in this range \( H \) field dependencies of such parameters, as magnetic permeability and susceptibility demonstrate weakly expressed non-sharp extreme. From the experiment, it is also evident that for the studied samples (as quasisolid magnetics) the transition value \( L/D = [L/D] = 10−12 \), i.e., significantly lower than for solid samples, particularly those made of steel. The dependence of demagnetizing factor data on \( L/D \) has been obtained for "short" samples (1 \( \leq L/D < [L/D] \)). In addition, eligibility of approximation by exponential expression has been shown for this data.

1. Introduction
In order to solve many scientific and practical problems associated with the use of heterogeneous (particularly porous) ferromagnet-bodies (mostly granulated: grains, granules, powders [1-11]), it is often sufficient to study them within the so-called macro-model of an effective medium [3]. Attempts have been made a long time ago [3,6,7] to implement it, i.e., to obtain data on certain magnetic parameters of a porous body that is similar to a modeled quasisolid body.

Such quasisolid bodies, as well as solid (homogeneous to a certain extent) bodies widely used for various purposes, usually appear to be "short", i.e., have a similar size in three typical directions. Therefore, magnetic properties of any quasisolid "short" body (usually taking the shape of a container, in which the corresponding granular medium is placed) are individual even for the environments identical in quality and structure – due to occurrence of demagnetizing factor that depends on the shape and specific sizes of this body. Moreover, the fact that deserves special attention and clarification is that suppression degree of magnetic properties of a "short" body by demagnetizing factor can be quite significant in comparison with potential properties, specifically the magnetic properties of a quasisolid material of such body. These are the properties of the same sample-body, but sufficiently "long" or having a typical toroidal (which excludes the occurrence of a demagnetizing factor in general) shape, as it is usually assumed in experimental studies of solid samples.
However, as for the individual (in terms of characteristic geometrical parameters) magnetic properties of "short" porous bodies that are used on a practical level (also to evaluate the demagnetizing factor), such information (which has to be based on the corresponding experimental dependencies families required for objective analysis) is still very limited, and certain knowledge already available in this area [6,7,12] requires extensive and in-depth study. This information would also be extremely relevant for objective testing of an ever-growing amount of different and often inconsistent computer modeling results (which undoubtedly allow to significantly increase the speed of obtaining data), for timely correction and improvement of modeling approaches (which is unfortunately almost absent so far).

To obtain such data on magnetic properties for both solid and porous samples, i.e., detailed not only in terms of magnetizing field strength but also and especially in terms of sample sizes (particularly of typical cylindrical shape), it is enough to have experimental data on magnetic induction in the samples: that data can be obtained with the use of a ballistic method, for instance [6,13,14]. Herewith, it should be mentioned that in case of studying a very common modification of cylindrically shaped sample with length L and diameter D, it is customary to use a generalized parameter of such shaped sample geometry – relative length L/D [1,14–19].

2. Results of the experiments and their analysis

The induction data have been obtained while conducting experiments (with the use of ballistic method) for cylindrical granular samples placed in a solenoid, the length of which was much longer than the length of the samples themselves. It was a filling of stainless ferromagnetic balls with an 8 mm diameter in a non-ferromagnetic tubular casing with an inner diameter of D = 40mm. The ranges of varied key parameters in the experiments, such as magnetizing field strength H and the relative length L/D of the samples were as follows: H = 9.4–47.2kA/m and L/D = 1–16. The induction data (which were then used to determine magnetic permeability, susceptibility and magnetization of the samples) were found as a quotient of the measured values of magnetic flux through a kink embracing the sample in its middle part divided by the kink area and number of its turns.

The experimental results in the form of dependencies families, demonstrating the nature and influence of field strength H and the relative length L/D, are shown in Figure 1a,b. In this case and further, it is convenient to use the following type of designation of the induction and other magnetic parameters, as implemented in [12]. It can be taken into account that for rod samples of various relative length L/D it is reasonable to use concept of transitional (criterion) value L/D = [L/D], indicating the existence of two ranges with fundamental differences in the behavior of magnetic parameters of the samples, specifically the range L/D ≥ [L/D] and the range L/D < [L/D]. For more certainty in these (Figure 1a,b) and following calculations, it is reasonable to introduce some differences in the designations of their magnetic parameters while keeping the corresponding sample names ("long" and "short"). With regard to "long" samples (L/D ≥ [L/D]), it is convenient to leave the traditional symbols for such magnetic parameters as induction, magnetic permeability, magnetic susceptibility and magnetization (for example B, μ, χ, M), because here, as it has been already stated, values of these parameters correspond to values of magnetic parameters of the material samples (quasisolid for the granulated samples). In case of "short" samples (L/D < [L/D]), it is reasonable to use traditional symbols of the corresponding magnetic parameters with an additional distinction, for instance, by adding the "s" (sample) index: B_s, μ_s, χ_s, M_s.
Figure 1. The experimental data of magnetic induction values in cylindrical samples of ball filling: a) in dependence from magnetizing field strength $H$ at various relative length values $L/D$ of sample (1 – $L/D = 16$; 2 – 9,4; 3 – 8,3; 4 – 6,8; 5 – 5,4; 6 – 4,1; 7 – 3,1; 8 – 2; 9 – 1); b) in dependence from relative length values $L/D$ of sample at various magnetizing field strength $H$ (1 – $H = 47,2$ kA/m; 2 – 37,7; 3 – 28,3; 4 – 18,9; 5 – 9,4). At $L/D \geq 10$–12, i.e. for "long" samples, induction data: symbol $B$, at $L/D < 10$–12, i.e., for "short" samples: symbol $B_s$.

In order to show more precisely the role of the relative length $L/D$ of the samples in the formation of their magnetization behavior, it is sufficient to transform the induction data from Figure 1a, as it is shown in Figure 1b. It is obvious that when there is a region of induction growth (herein the induction in "short" samples, meaning $B_s$) with increasing $L/D$, but with a noticeable decrease in the intensity of this growth. However, the maximum possible limits of induction (particularly the induction in relatively "long" samples with almost no demagnetizing factor, i.e., $B$ values equivalent to the induction in the sample's quasisolid material) can be achieved with almost a sole, identity with clear value $L/D = [L/D] \approx 10$–12 (Figure 1b). This is the transitional (criterion) value of such relative length samples for their magnetization. With $L/D \geq [L/D]$, the sample is sufficiently "long" that is fairly from the observed self-similarity area of the induction values $B$ (Figure 1b): it allows to consider the magnetic induction in the samples of such relative length $L/D$ (starting at least with the value $L/D = [L/D] \approx 10$–12) to be equivalent to magnetic induction in their quasisolid material.
The obtained result that is in accordance with [6,12], allows to point out the significant fact, related to the considered feature of magnetic properties of granular samples: such values of their relative length \( \frac{L}{D} = [L/D] \) within the taken magnetizing field strength range \( H \) are achieved almost independently of the value \( H \) (Figure 1b).

The magnetic properties of the studied granular (poly-ball) samples are also demonstrated by corresponding field dependencies of magnetic permeability of the samples (Figure 2a). The permeability data for "long" \( \mu \) and defined "short" \( \mu_s \) samples, required to obtain these dependencies, can be found with ease by the use of the induction data \( B \) (if \( L/D \geq [L/D] \)) and \( B_s \) (if \( L/D < [L/D] \)) in Figure 1 and performing calculations in accordance with the physical relations:

\[
\mu = \frac{B}{\mu_0 H}, \quad \mu_s = \frac{B_s}{\mu_0 H},
\]

where \( \mu_0 = 4\pi \times 10^{-7} \) H/m – magnetic constant.

The magnetic permeability field dependencies family (\( \mu \), if \( L/D < [L/D] \)) is limited at the top by the \( \mu \) curve (Figure 2a) that characterizes the magnetic permeability of the (quasisolid) material sample exactly. Moreover, the existence of transitional (criterion) relative lengths with a defined value of \( L/D = [L/D] \approx 10–12 \) and permeability self-similarity areas at \( L/D \geq [L/D] \) are also precisely shown in the corresponding magnetic permeability dependencies (on \( L/D \)) of the samples (Figure 2b).

**Figure 2.** The magnetic permeability values of cylindrical samples of ball filling obtained by data on Figure 1 subject to (1): a) in dependence from \( H \) at various \( L/D \); b) in dependence from \( L/D \) at various \( H \). At \( L/D \geq 10–12 \) permeability data: \( \mu_s \), at \( L/D < 10–12 \): \( \mu_s \).

The obtained field dependencies of magnetic permeability (Figure 2a) precisely depict areas around weakly expressed permeability extrema in taken field strength range \( H = 9.4–47.2 \) kA/m, i.e., areas of almost equal (stable within \( H \)) permeability values. This is also indirectly indicated by the fact of the close distribution of all (obtained in this \( H \) range) magnetic permeability dependencies on the relative
length $L/D$ of the samples (Figure 2b): these dependencies are relatively "concise", almost not stratified within $H$.

Magnetic properties of the studied granular samples are also characterized by the field dependencies of magnetic susceptibility of the samples shown in Figure 3a. The susceptibility data required to obtain these dependencies for "long" $\chi$ and defined "short" $\chi_s$ samples can be found by the use of the permeability data $\mu$ (if $L/D \geq \lfloor L/D \rfloor$) and $\mu_s$ (if $L/D < \lfloor L/D \rfloor$) in Figure 2 and performing calculations in accordance with the physical relations:

$$\chi = \mu - 1, \quad \chi_s = \mu_s(\mu - 1)/\mu.$$  

(2)

The obtained field dependencies of magnetic susceptibility (Figure 3a) can be used to make judgments similar to previous ones in Figure 2a by analyzing the field dependencies of magnetic permeability. Here it is clearly observed (Figure 3a) that is taken field strength range $H = 9.4-47.2$ kA/m field dependencies of susceptibility reflect areas around weakly expressed extrema, i.e., areas of almost equal (stable within $H$) susceptibility values. The same is evidenced by the obtained dependencies of magnetic susceptibility of samples on their relative length $L/D$ (Figure 3b). It can be clearly observed that in the taken $H$ range, these dependencies (Figure 3b) are distributed compactly, also "concise" (same as the permeability curves in Figure 2b), i.e., almost not stratified within $H$. And, of course, the magnetic susceptibility dependencies (on $L/D$) of the samples shown in Figure 3b also confirm the transitional (criterion) value of the relative length $L/D = [L/D] \approx 10-12$ and the existence of self-similarity areas of susceptibility at $L/D \geq \lfloor L/D \rfloor$. 

Figure 3. The magnetic susceptibility values of cylindrical samples of ball filling obtained by data on Figure 2 subject to (2): a) in dependence from $H$ at various $L/D$; b) in dependence from $L/D$ at various $H$. At $L/D \geq 10-12$ susceptibility data: $\chi$ at $L/D < 10-12$: $\chi_s$. The first of the relationship is well-known, and the basis for the second (for "short" samples) is available in [12]. It should be noted that in some works the calculation of magnetic susceptibility of "short" samples is unnecessarily simplified during processing and analysis of experimental data, for example in [13] calculation is done as for "long" sample, while in fact $\chi_s \neq \mu_s - 1$. This, of course, leads to errors in the corresponding results.
Magnetic properties of the studied granular samples as well as confirmation of the existence of transitional (criterion) relative length value $L/D = [L/D] \approx 10–12$ and self-similarity areas at $L/D \geq [L/D]$ can also be evaluated by their dependencies of magnetization on $H$ (Figure 4a) and $L/D$ (Figure 4b). The magnetization data $M$ of "long" and $M_s$ of defined "short" samples required to obtain these dependencies and can be found by the use of susceptibility data $\chi$ (for $L/D \geq [L/D]$) and $\chi_s$ (for $L/D < [L/D]$) in Figure 3 and performing calculations according to the physical relations:

$$M = \chi H, \quad M_s = \chi_s H.$$  \hspace{1cm} (3)

The obtained field dependencies of magnetization in Figure 4a (as well as the induction in Figure 1a), judging by their trends, indicate (as in [12]) the absence of signs of magnetic saturation of such (granular) magnetics. Therefore, with increasing intensity of field strength $H$ these dependencies, still continue to increase significantly though with decreasing intensity that is not typical (for solid magnetics) in such cases. At the same time, the fact that for granular magnetics (in contrast to solid ones) the magnetic saturation is not achieved with increasing $H$ (up to $H = 40–50$kA/m) is evident also by the example of limit magnetization field dependence $M$ (curves 1 and 2 on Figure 4a), meaning exactly the dependence for quasisolid material sample. Otherwise, there would be (starting with a certain, relatively small value of $H$) a distinct area of self-similarity (here it is absent), as usually observed for the material of solid, in particular steel samples.

**Figure 4.** The magnetization values of cylindrical samples of ball filling obtained by data in Figure 3 subject to (3): a) in dependence from $H$ at various $L/D$; b) in dependence from $L/D$ at various $H$. At $L/D \geq 10–12$ magnetization data: $M$, at $L/D < 10–12$: $M_s$.

Using available data (in Figure 1–3) for induction $B$, or permeability $\mu$, or susceptibility $\chi$ of "long" sample (for $L/D \geq [L/D]$) and data for induction $B_s$, or permeability $\mu_s$, or susceptibility $\chi_s$ of some "short" sample (for $L/D < [L/D]$), it is possible to obtain demagnetizing factor data $N$ for "short" samples by the use of any of these expressions:
\[ N = [(\mu / \mu_s) - 1]/(\mu - 1) = [(B / B_s) - 1]/(B / \mu_0 H - 1), N = 1/\chi_s - 1/\chi, \]  

(4)

the latter is well-known, and the basis for the first expressions (that are mutually related through (1)) is available in [12].

The values of parameter \( N \), obtained from (4) by the use of data of Figure 1–3, are presented in Figure 5a – depending on the parameter \( L/D \) for "short" samples: from \( L/D = 1 \) to \( L/D \rightarrow [L/D] \). Additionally, it is reasonable to use \( B_s, \mu \), and \( \chi \) values that are not so close to the corresponding \( B, \mu \) and \( \chi \), values for calculations of \( N \) in cases when "short" samples are getting close (length-wise) to "long" ones because quite significant biased jumps of \( N \) values are possible, even with a small error in defining values of \( B_s, \mu, \) and \( \chi \). Judging by the trend of obtained local (relatively densely distributed) data it can be seen (Figure 5a) that the corresponding dependence of \( N \) on \( L/D \) is close to a single one (without stratification within \( H \)), in spite of significant differences in the given values of field strength \( H \): from 9.4kA/m to 47.2kA/m.

Figure 5. The dependence of demagnetizing factor of cylindrical samples of ball filling: a) in dependence from the relative length of the sample; b, c) from its power function; calculations are obtained subject to (4) using data on Figure 1 (or Figure 2, or Figure 3); \( H = 9.4\text{–}47.2 \text{kA/m} \).

Before attempting to approximate the data in Figure 5a with an analytic (phenomenological) dependence, it is necessary to discuss in more detail and consider the conditions, under which these data are obtained.

In the beginning, it is related to peculiarities of the selected range of field strength \( H \) for conducting experimental studies.

As mentioned above, this range corresponds to the expressed (non-sharp) extreme zones of field dependencies (Figure 2, 3) of the magnetic permeability and susceptibility of the used poly-ball samples (and their quasisolid material). Thus, these dependencies here are characterized with almost equal (almost stable within \( H \)) values of permeability or susceptibility. Therefore, at least in this range of \( H \), the influence of \( H \) on the values of the demagnetizing factor \( N \) is not relevant.

The following stage relates to the (seemingly) comparatively narrow range, used for the relative length of the samples \( L/D \approx 1\text{–}10 \) – in comparison with the theoretically possible unlimited range \( 0 < L/D < \infty \).

To negate this doubt, the following can be stated. Quite "short", basically disk type samples \( (0 < L/D < 1) \) should be considered as a separate, independent class of samples (with corresponding approaches to the targeted acquisition of magnetic parameters, including \( N \)). Then in the remaining possible range of \( 1 \leq L/D < \infty \) the narrowed range of \( L/D \) (from \( L/D = 1 \) to \( L/D \approx 10\text{–}12 \)) becomes to be of most interest in terms of obtaining an expression for \( N \).

Illustrated in Figure 1–4 trends of dependencies of magnetic parameters on \( L/D \) with clearly distinguished transitional (into self-similarity area of these parameters) value \( L/D = [L/D] \approx 10\text{–}12 \)
testify, in particular, about limitation of $L/D$ range from the right (to $L/D \approx 10–12$). In the identified self-similarity area $L/D \geq [L/D]$ the magnetic parameter values almost correspond to those for a "long" (theoretically $L/D \rightarrow \infty$) sample with vanishingly small values of $N$: $N \rightarrow 0$.

Very small $N$ values at $L/D \rightarrow 10–12$ are also indicated with comparative estimates of magnetic susceptibility of "short" sample $\chi_s$ and its material $\chi$, even if based on results obtained for solid cylindrical magnetics [19].

Thus, according to [19], for such magnetics with relatively low magnetic permeability of the material $\mu = 5–10$, at $L/D \approx 10$ the values of the demagnetizing factor $N$ are equal to $N \approx (0.8–1) \cdot 10^{-2}$.

Hence, with the use of the well-known expression (the second one in (4)), transformed as:

$$\chi_s / \chi = 1/(1 + N\chi), \quad (\chi - \chi_s) / \chi = N\chi / (1 + N\chi), \quad (5)$$

allows to estimate the mutual relation of $\chi_s$ and $\chi$ parameters, as $\chi_s, \chi$, and also their relative difference, as $(\chi - \chi_s) / \chi$.

In particular, taking into account the $\chi$ values for quasisolid material of poly-ball samples of interest at the level of $\chi \approx 6$ and less (Figure 3) and the value (from the above-mentioned ones for solid samples) $N \approx 0.9 \cdot 10^{-2}$, with (5) it is easy to verify that for the sample with $L/D \approx 10$: $\chi_s / \chi \approx 0.95$, and $(\chi - \chi_s) / \chi \approx 0.05 (~5 \%)$.

For the (solid) sample with slightly longer relative length, $L/D \approx 12$ at the same comparatively low magnetic permeability of its material ($\mu = 5–10$) the value of the demagnetizing factor according to [19] decreases to $N \approx 0.55 \cdot 10^{-2}$. It means that for the same value of magnetic susceptibility of a quasisolid material (at the level of $\chi \approx 6$ and less) the following values are inherent for the sample ($L/D \approx 12$): $\chi_s / \chi \approx 0.97$, $(\chi - \chi_s) / \chi \approx 0.03 (~3 \%)$.

When further increasing $L/D$ of the sample, values of $\chi_s / \chi$ are getting closer to one, while values $(\chi - \chi_s) / \chi$ are getting closer to zero. For instance, having an $L/D \approx 15$ for a sample from the same $\mu$ material according to [19]: $N \approx 0.4 \cdot 10^{-2}$ and then $\chi_s / \chi \approx 0.98$, and $(\chi - \chi_s) / \chi \approx 0.02 (~2 \%)$.

Therefore, this evaluation analysis additionally shows that the search for the dependence of $N$ on $L/D$ with $L/D > 10–12$ makes no sense for samples with relatively low values of magnetic permeability and susceptibility of their material when the mutual difference between $\chi_s$ and $\chi$ decreases while increasing $L/D$, and becoming comparable with measurement errors.

Consequently, based on the above, a conclusion about the increased interest in the range of relative length $L/D \approx 1–10$ for quasisolid samples can be considered justified. It covers a fairly wide and, to a certain extent, independent class of samples-magnetics that possess magnetic properties to be studied, particularly to obtain data on their demagnetizing factor $N$.

As for the data presented in Figure 5a in the form of dependence of the demagnetizing factor $N$ of quasisolid samples on their relative length $L/D$ exactly in this $L/D$ range, there is a possibility to obtain an approximating dependence. Thus, according to [12], these data should be presented in semi-logarithmic coordinates, and the $L/D$ parameter itself—in the form of power dependence: such as a radical, meaning $\sqrt{L/D}$. Then it is not difficult to ensure that the data $N$, depicted in such coordinates (further considering a physically justified checkpoint, that is: $N \rightarrow 1$ at $L/D \rightarrow 0$), are subject to the expected quasilinearization in considered $L/D$ range (Figure 5b). This provides the basis for their phenomenological approximation by the exponential expression of:

$$N = \exp[-k(L/D)^n], \quad (6)$$

that is true for the phenomenological parameter $k \approx 1.6$.

In this expression, which should be taken as one of the options to find the desired relation between $N$ and $L/D$ for "short" granular magnetic-bodies, it is reasonable to use the power index of $L/D$ not as $n \approx 0.5$, but $n \approx 0.6$. Then in such semi-logarithmic coordinates (Figure 5c) data $N$ is even slightly better approximated (with the phenomenological parameter $k \approx 1.4$).

3. Conclusion

The induction data dependent on the magnetizing field strength $H = 9.4–47.2$ kA/m has been obtained for granular ferromagnetic samples (for their relative length range $L/D = 1–16$) with cylindrical poly-


ball samples used as an example. And subsequently with this data, magnetization, magnetic permeability, and susceptibility of the samples (that appeared in the area of non-sharp peaks of their field dependencies, therefore having almost stable values) have been found.

It has been revealed that in taken $H$ range the field dependencies of induction and magnetization show a continuous noticeable (only with a slightly decreasing intensity) growth, which indicates the absence of magnetic saturation of such granular (as opposed to solid) magnetics.

The transitional (criterion to a certain extent) value $L/D = [L/D] \cong 10–12$, has been determined. Starting from this value, the magnetic parameters of the sample and its material (quasisolid) correspond to each other.

The validity of the exponential expression for the demagnetizing factor of "short" ($1 \leq L/D < 10–12$) granular samples have been shown: in this expression, at the specified values of field strength (where almost stable values of magnetic permeability of the material have been reached: 6.7–7.2), the argument can be a power function of the $L/D$, particularly as a radical of this ratio.

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