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REMARKS ON SELECTING LENGTH OF CYLINDRICAL SAMPLE TO DETERMINE MAGNETIC PROPERTIES OF ITS MATERIAL

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Abstract

When experimentally studying magnetic properties of the ferromagnetic materials, preferences are often given to a more convenient method involving the use of sufficiently long cylindrical samples with the *L* length and the *D* diameter placed in the solenoid field as an alternative to the method based on using classical samples of the toroidal shape (to exclude manifestations of the demagnetizing factor). Currently, required justification is practically missing for specific values of the relative *L*/*D* length, which would indicate such [*L*/*D*] values (for $L/D \geq [L/D]$), at which magnetic properties of a sample (already long enough) correspond to magnetic properties of its material. While the existing recommendations such as [*L*/*D*] = 50 are postulated, let us note that relevant experimental studies of magnetic properties of the cylindrical samples with the *L*/*D* parameter targeted variation were not made. An attempt was made to fill this gap. For cylindrical steel samples with the different *L*/*D* values (from 1 to 50), families of the *B* magnetic induction and of the μ permeability field dependencies were obtained experimentally using the ballistic method. The sought [*L*/*D*] values were determined from the *B* and μ dependencies on the *L*/*D* by the junction abscissa of the ascending and self-similar branches. It was established that in the accepted field strength in the range of *H* = 0.94–54.2 kA/m magnetizing field, the [*L*/*D*] parameter is a variable substantially depending on *H* (and/or μ). It varies from [*L*/*D*] = 10–15 at *H* = 54.2 kA/m (μ = 30) to [*L*/*D*] = 50–60 at *H* = 4.7 kA/m (μ = 270).

Keywords

Relative length, sample, induction field dependence, permeability field dependence, transient value

And at $H < 4.7$ kA/m, $[L/D] > 50–60$, i.e., more than is commonly believed. Thus, it was stated that the data on magnetic properties obtained when using even long samples ($L/D = 50$) and declared as data on the magnetic properties of the corresponding material, are only close to those with $H < 4.7$ kA/m. Phenomenological expressions were obtained for the $[L/D]$ determination: exponential with the H argument and logarithmic with the μ argument

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Introduction. When a short ferromagnetic body is magnetized, i.e., a sample of relatively comparable size in three dimensions (often within the same order of magnitude), the demagnetizing factor appears, due to which magnetic properties of the sample are being significantly suppressed in comparison with potential properties inherent in its material. And these properties, as is known, are found only when implementing such an experimental method of studying a sample, which would exclude manifestation of the demagnetizing factor. For this purpose, in physics (and in the applied electrical engineering), classical samples of a special toroidal shape are usually used, which excludes manifestation of the demagnetizing factor in principle.

Taking into consideration difficulties and limitations arising in this case (both in sample preparation and in experiment efficiency), the method based on using a cylindrical sample placed in the field, for example, a solenoid, appears to be more convenient in the practice of physical research methods both constructively and technologically for this purpose. But in this case (when it comes to studying magnetic properties not of the sample itself, but of its material), it is necessary to have a sufficiently long sample, i.e., a sample of such a length, when the sample demagnetizing factor becomes vanishingly low.

It is generally accepted that for cylindrical samples of the L length and D diameter used in such operational method, this is achieved, as it were with the single $L/D = [L/D] = 50$ value [2–4], when their characteristic self-sufficient geometry parameter is the L/D ratio [1–8].

However, in regard to the mentioned and to a certain extent already established opinion only as the postulated concept could be mentioned. Unfortunately, this concept corresponding argumentation, as well as much-needed study of the problem on the importance (and with possible variability, values) of the $L/D = [L/D]$ relative length of a cylindrical sample really long enough is practically missing.

Meanwhile, detailed information on approximation to the self-similarity characteristic region (up to explicitly reaching this region) of any key magnetic parameter, in particular the B induction in samples under study and/or their μ magnetic permeability, would be exhaustive increasing L/D step by step and, of course, performing studies at various values of the H applied magnetic field. Obtaining information on the pre-self-similar and self-similar regions, the sample could be considered rather long with practically missing demagnetizing factor using the corresponding abscissa of the $L/D = [L/D]$ transition point (which formed the basis for the present work goal and objectives). This approach proved its importance in obtaining the $L/D = [L/D]$ values by the example of appropriate studies of such specific samples as granular magnets [9, 10].

Research methods, results obtained and discussion. Necessary information about a sufficiently long sample with the $L/D = [L/D]$ inherent transition value could be obtained by experimentally determining values of one or another magnetic parameter of a cylindrical sample (in particular, a steel one, alternately using samples of the L/D different relative length) depending on the intensity of the H magnetizing field, and more clearly — depending on the L/D.

Out of widely practiced and well-proven methods for determining magnetic parameters (which could be taken as the basis for analysis in establishing the $L/D = [L/D]$), for example, ballistic, ponderomotive, vibration, etc. [3, 4, 11–20], preference in this case should be given to the ballistic method, which makes it possible to relatively quickly find the B magnetic induction in the sample under study. In this case, it is the ratio of the measured (by a milliwebermeter) magnetic flux through the loop covering the sample in its middle part to the loop area and to the number of its turns.

The obtained B data make it possible to determine other magnetic parameters of the samples under study, in particular, their μ magnetic permeability, using the known dependence:

$$\mu = \frac{B}{\mu_0 H}, \tag{1}$$

where $\mu_0 = 4\pi \cdot 10^{-7}$ H/m is the magnetic constant.

To magnetize the samples, a rather long, in comparison with the longest sample, sectional multilayer solenoid (almost 0.8 m long) was used, which made it possible to place the sample under study exactly in its working part, i.e., to exclude those solenoid frontal inner parts, where there was a characterristic decrease in intensity of the field created by it. The magnetizing field *H* strength ranged from 0.94 to 54.2 kA/m.

To determine the desired *L*/*D* = [*L*/*D*] transition value, it is necessary initially to obtain a family of the *B* dependences on *H* (sample magnetization curves with different *L*/*D*), when with the *L*/*D* significant increase field dependences are located higher and higher certainly striving for the *B* limiting dependence on *H*.

Fig. 1 shows experimentally obtained field dependences of the *B* induction in various (*L* = 12–600 mm length) cylindrical steel specimens with the *D* = 12 mm diameter, i.e., in the range of the relative specimen length *L*/*D* = 1–50. In this case, the last figure in this *L*/*D* range corresponds to the value indicated in [2–4] (seemingly uniform), at which, according to the same works, the sample demagnetizing factor practically disappears, i.e., magnetic properties of a sample with this length should correspond to its material magnetic properties.

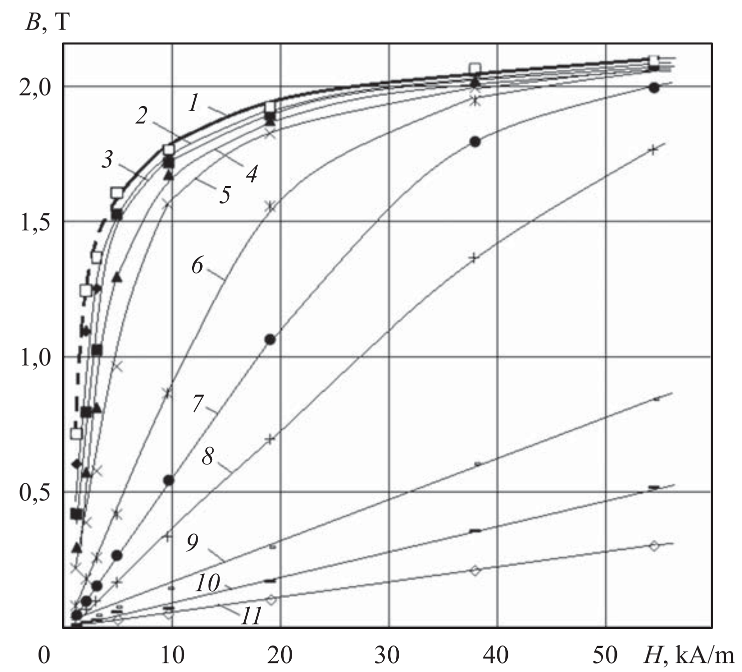

Fig. 1. Magnetic induction in cylindrical steel samples depending on the *H* field strength at different relative length of the *L*/*D* sample *L*/*D* = 50, 43, 32, 25, 19, 11, 8, 5.5, 3, 1.8 and 1 (curves *1–11* respectively)

Fig. 1 demonstrates that in addition to quantitative difference between the *B* induction dependences in samples on the *H* field strength obtained at different values of the samples' relative *L*/*D* length, difference in trends of these dependences is quite noticeable. Thus, the *B* magnetization curves versus H at comparatively low L/D values are weakly increasing. And at comparatively high and high L/D values, they become steeply increasing, more and more (with the increasing L/D) approaching the known steel magnetization curves.

Having a fairly complete (see Fig. 1) family of experimental field dependences of the B induction, for now, nevertheless, it is recommended to refrain from judgments about the already achieved limiting magnetization curve (see Fig. 1, curve *1*) up to obtaining more informative for this corresponding family of the B dependences on L/D (for different H). Moreover, until a family of the B dependences on L/D is obtained, it is recommended to refrain from making specific judgments about the $L/D = [L/D]$ value (judging by Fig. 1, this is not a fixed value, as was previously assumed [2–4]), which would make it possible to be considered as rather long.

Indeed, based only on the family of dependencies shown in Fig. 2, when at $L/D \geq [L/D]$ the B dependences on L/D should become self-similar (here they are individually self-similar), it is possible to give a completely objective assessment of the $L/D = [L/D]$ values, and using them to provide an objective assessment of the limiting magnetization curve in Fig. 1.

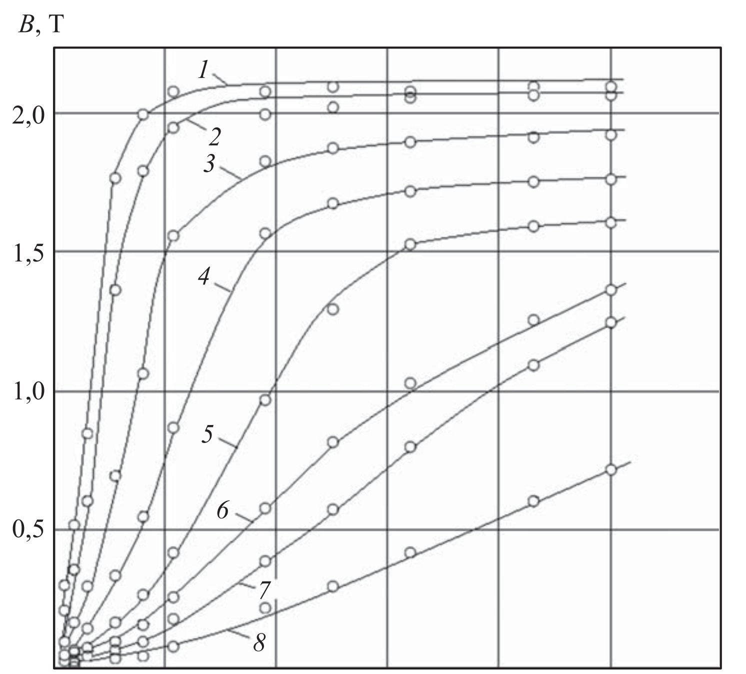

Fig. 2. Magnetic induction dependence in cylindrical steel samples on the L/D sample relative length at different field strengths H = 54.2, 37.7, 18.9, 9.4, 4.7, 2.8, 1.9 and 0.94 kA/m (curves *1*–*8* respectively)

Thus, the obtained B dependences on L/D (see Fig. 2) clearly demonstrate information about the $L/D = [L/D]$ values, starting from which, i.e., at $L/D \geq [L/D]$ (in the regions of B self-similarity), the sample could be considered rather long, and the B values are individually (for certain H values) limiting and corresponding to the B values in the sample material itself.

In this case, an important feature, not previously noted in the literature, is that the $L/D = [L/D]$ values depend on the H magnetizing field strength. Fig. 2 shows that the $L/D = [L/D]$ estimated values are: $[L/D] \cong$ 10–15 at H = 54.2 kA/m; $[L/D] \cong$ 15–25 at H = 37.7 kA/m; $[L/D] \cong$ 30–40 at H = 18.9 kA/m; $[L/D] \cong$ $\cong$ 40–50 at H = 9.4 kA/m; $[L/D] \cong$ 50–60 at H = 4.7 kA/m. As for the $L/D =$ $= [L/D]$ values for samples magnetized in a field of the $H \leq 4.7$ kA/m strength, the data in Fig. 2 indicate that $[L/D] >$ 50–60. It should be noted that these values clearly exceed the $L/D = 50$ value specified in [2–4], which is qualified as sufficient to obtain information on magnetic properties of the sample material itself.

The noted mutual correspondence in values of such parameters as the sample transitional (from the B increasing induction region to its self-similarity region) relative length $[L/D]$ and the H magnetizing field strength, make it possible to consider a kind of correlation of the downward dependence between them (Fig. 3, *a*).

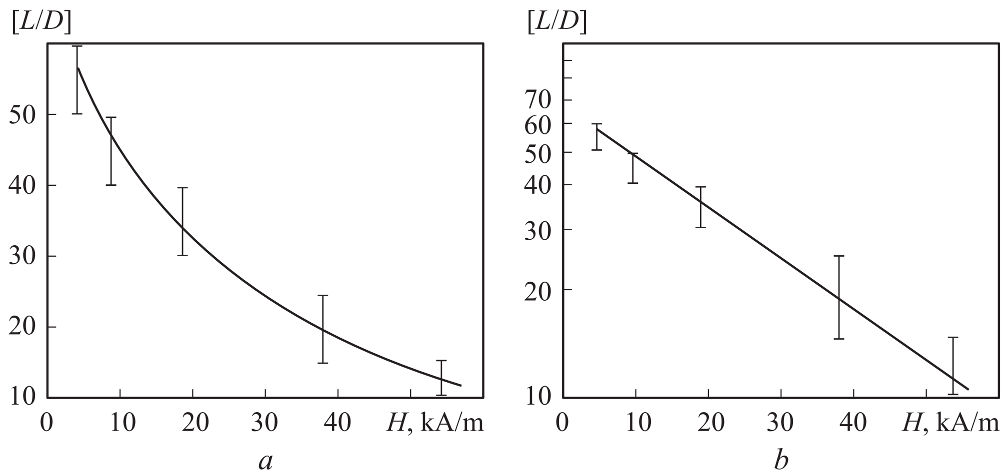

Fig. 3. On correlation between the sample relative length $[L/D]$ transient value and the H field strength; *a* and *b* are ordinary and semilogarithmic coordinates

In addition, this dependence being presented in semilogarithmic coordinates (Fig. 3, *b*) quasi-linearizes quite perfectly here indicating existence (at least in the accepted H range) of a phenomenological relationship in the exponential form:

$$\left[\frac{L}{D}\right] = A_H \exp\left(-\frac{H}{H_x}\right), \tag{2}$$

where A_H and H_x are the phenomenological parameters, which values (based on actual data in Fig. 3) constitute: A_H = 67, and H_x = 30 kA/m (if H is in kA/m) or H_x = 30 000 A/m (if H is in A/m).

Based on dependences presented in Fig. 2, subsequent connections (see Fig. 3) and expression (2), a more detailed characteristic could be provided of the magnetic induction field dependence obtained for the longest sample (L/D = 50) (see Fig. 1, curve *1*) from the point of view of its correspondence to field dependence of the magnetic induction inherent in the sample material.

Thus, this B induction field dependence could not be recognized as limiting throughout its entire length (fully satisfying the $L/D \geq [L/D]$ condition), i.e., in the entire selected range of H = 0.94–54.2 kA/m. The B limiting field dependence could be considered only in its tail section at $H \geq 4.7$ kA/m ≈ ≈ 5 kA/m. This area (curve *1*, see Fig. 1) is marked with a somewhat thickened solid line. And its initial section at $H < 4.7$ kA/m, as not satisfying the $L/D \geq$ $\geq [L/D]$ requirement ($[L/D]$ values are higher compared to value specified in [2–4] ~ 50) is shown by the *1* dashed curve in Fig. 1.

Taking into consideration relationship (1), from families of the B induction dependences (see Figs. 1 and 2 for H and L/D), it is simple to obtain the corresponding μ magnetic permeability dependence families shown in Figs. 4 and 5 (H is the post-extremal part of the μ field dependence in Fig. 4 for the accepted range of field strength).

They also make it possible to judge the $L/D = [L/D]$ previously mentioned values by transition of the μ curves from L/D in Fig. 5 to the self-similar region, but, as before, only at $H \geq 4.7$ kA/m. In turn, this allows judging incomplete correspondence with the one in Fig. 4 (curve *1*), as it were, the μ permeability field dependence (the longest sample L/D = 50) of the μ field dependence, which is inherent in the sample material. This dependence (see Fig. 4, curve *1*) should be considered as limiting (corresponding to the sample material field dependence) only partially at $H \geq 4.7$ kA/m (tail section is highlighted with a slightly thickened solid curve), while at $H < 4.7$ kA/m (initial segment, dashed curve) it could not be considered as limiting.

Having data shown in Figs. 4 and 5 on the μ magnetic permeability (depending on the H field strength and the L/D relative length), it is possible to get back to the considered question on the observed alteration in the L/D = = $[L/D]$ relative length transition value (see Fig. 3), but now depending not on H, but on μ.

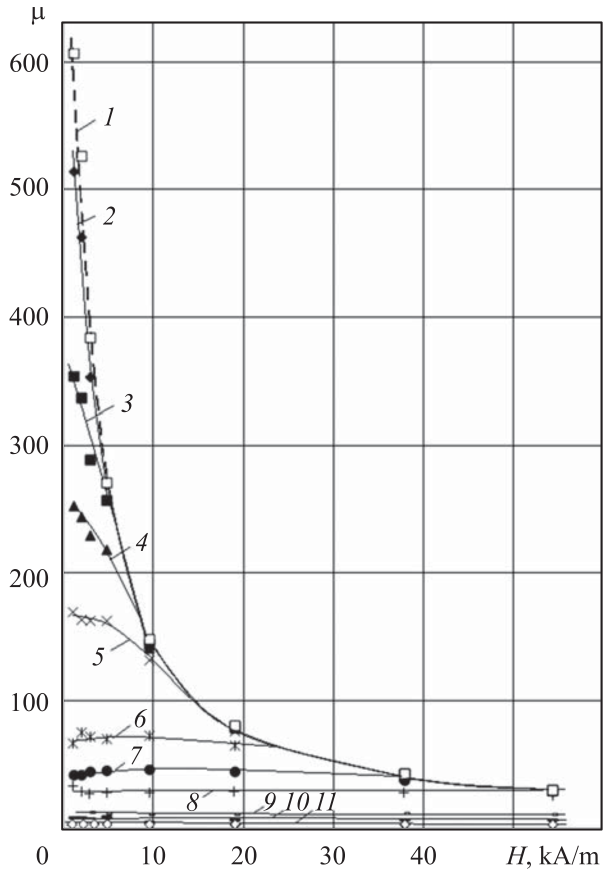

Fig. 4. Magnetic permeability of samples depending on the *H* field strength at different values of the samples' relative length L/D = 50, 43, 32, 25, 19, 11, 8, 5.5, 3, 1.8 and 1 (curves *1–11* respectively)

For this purpose, the $[L/D]$ data (the same as in Fig. 3, *a*) are presented in Fig. 6, *a*, but with the μ abscissa (but not *H*, as previously). And the transition from *H* to μ was made on the basis of data in Fig. 4 (curve *1*, which tail is shown by the thickened line).

If the obtained dependence in Fig. 6, *a* is represented in semilogarithmic coordinates (Fig. 6, *b*), it could be determined that in such coordinates it quasilinearizes rather easily, thus indicating existence of a logarithmic (in the $H = 4.7–54.2$ kA/m range and the corresponding range $\mu = 270–30$) phenomenological connection:

$$\left[\frac{L}{D}\right] = A_\mu \ln \frac{\mu}{k}, \quad (3)$$

where A_μ and k are the phenomenological parameters, here $A_\mu = 21$, $k = 18$.

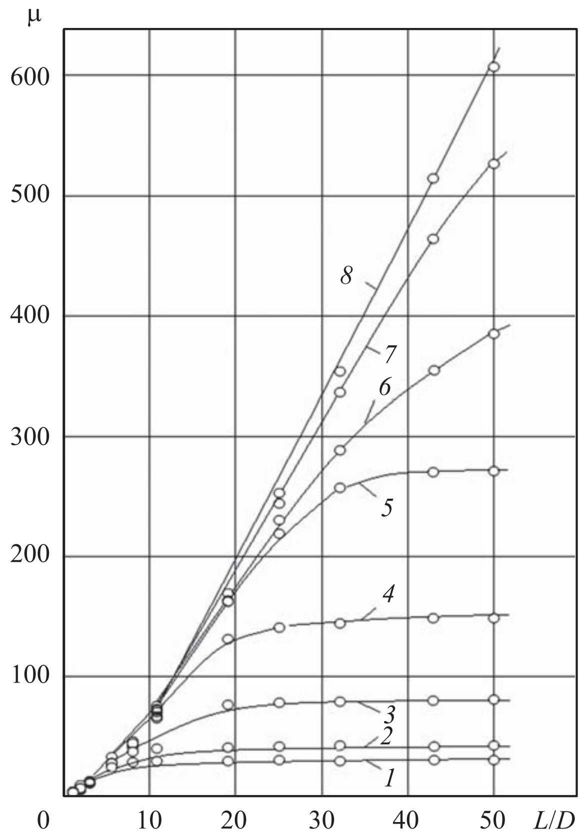

Fig. 5. Magnetic permeability of samples depending on the *L*/*D* sample relative length at different values of the field strength *H* = 54.2, 37.7, 18.9, 9.4, 4.7, 2.8, 1.9 and 0.94 kA/m (curves *1*–*8* respectively)

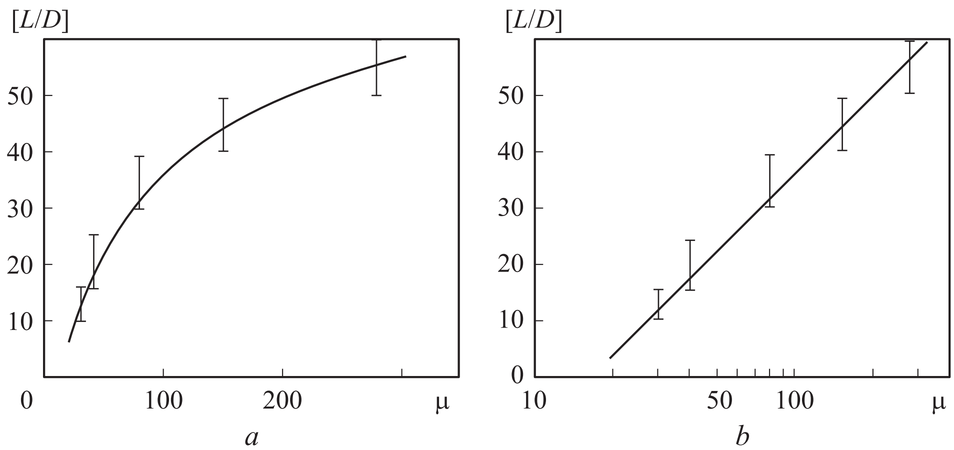

Fig. 6. On correlation between the sample [*L*/*D*] relative length transition value and the μ magnetic permeability of its material; *a* and *b* are ordinary and semilogarithmic coordinates

Thus, results presented and analysis thereof (according to both induction and permeability data) demonstrate that, when using a cylindrical sample to obtain direct information about its material magnetic properties, special attention should be paid to selecting the $L/D = [L/D]$ required relative sample length, not always relying on the accepted recommendation to use the $L/D = [L/D] = 50$ value. This value is not the only one (as, for example, for granular cylindrical samples [9]) mostly acceptable with sample magnetizing in a relatively narrow range of magnetizing field strength of $H \approx 5$–15 kA/m (according to Fig. 4, this corresponds to the range of magnetic permeability from $\mu \approx 270$–280 to $\mu \approx 90$–100). At $H > 15$–20 kA/m, the $[L/D] = 50$ value, although it is acceptable, seems to be excessive. And at $H < 5$ kA/m, it is not sufficient to consider such a sample sufficiently long (recall, when its magnetic parameters practically correspond to the sample material parameters). Ignoring this circumstance (which often happens in the practice of implementing such a physical research method) leads to an error in values of certain magnetic parameters specifically of the sample material, when obtaining reliable values of these parameters for the sample itself.

Conclusion. An objective requirement for a discussion is presented related to clarifications in application of the metal magnetic properties experimental research method based on using sufficiently long samples (alternative to the method using classical toroidal samples). In this regard, the work raises a question on the validity of existing concept (postulated) concerning the required value of ratio of the sample length to its diameter $L/D = [L/D] = 50$ (starting from which, magnetic parameters of the sample and its material correspond to each other), and the rationale for selecting the $L/D = [L/D]$ value is provided. The B magnetic induction dependence families (on field strength in the range of $H = 0.94$–54.2 kA/m) in steel samples and their μ magnetic permeability with L/D alteration from 1 to 50 were experimentally obtained and analyzed. The picture of dependences obtained, especially in the most indicative here coordinates with the L/D abscissa (for different H) made it possible to identify the $L/D = [L/D]$ values by these dependences characteristic exit to the self-similar region. Previously unreported fact was established that the $[L/D]$ values depend on H (and μ), and constitute: from $[L/D] = 10$–15 at $H = 54.2$ kA/m ($\mu = 30$) to $[L/D] = 50$–60 at $H = 4.7$ kA/m ($\mu = 270$). And at $H < 4.7$ kA/m ($\mu > 270$): $[L/D] > 50$–60, i.e., more than usually considered to be. Phenomenological expressions were obtained for $[L/D]$ with both H and μ arguments.

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