Micro- and nanoelectronics. Condensed matter physics

Микро- и наноэлектроника. Физика конденсированного состояния

UDC 537.621
https://doi.org/10.32362/2500-316X-2021-9-5-36-44

RESEARCH ARTICLE

Towards a model of chain-by-chain magnetization of a granular medium: a variant of magnetic diagnostics of chains of spheres

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Abstract. In addition to information on the magnetic parameters of inhomogeneous magnetics, in particular, granular magnetics usually studied within the framework of the quasi-continuous medium model, it is of no less interest to obtain information from the standpoint of the model, when the object of study is the characteristic elements of an inhomogeneous magnetic. According to the well-proven model of selective magnetization of a granular medium, the elements that make up this medium are chains of granules—straight and sinuous, always manifesting themselves in the direction of its magnetization. They perform the function of conductor channels of the generated magnetic flux through the granular medium. As a result, it is a kind of branched «bundle» of conductor channels. For any of the chains of granules, for example, granules-balls of radius R, conceptually significant are the magnetic parameters of its conditional cores with radius $r \leqslant R$, and these parameters, first of all, the magnetic permeability of quasi-continuous cores and magnetic induction in them, for different (in r) cores are variable, which requires appropriate magnetic diagnostics. To clarify the magnetic parameters of the conditional cores of a chain of granules-balls, as a physically self-sufficient element of a granular medium (i.e., in accordance with the model of chain-link magnetization of such a medium), it is practical to make measuring magnetic flux sensors in the core as circular sensors surrounding the contact point of granules-balls, however, not as traditional wire loops, but as circuits on thin printed circuit boards (with mounting holes) placed between adjacent balls. Based on the obtained data of the magnetic flux in cores of different radii r (r/R = 0.2–0.9) of a chain of spheres with a radius of R = 20 mm, the values of the magnetic flux density B in them, as well as their magnetic permeability μ, were determined when the chain is magnetized in the solenoid by a field of strength from 4.8 to 54.5 kA/m. It is shown that with formal thickening of the cores, the values of B and μ decrease due to a decrease in the volume of the ferromagnet in the core, and for the limiting core ($r/R \to 1$), i.e., for the chain as a whole, they correspond to the values of B and μ for a poly-ball backfill medium.

Keywords: magnetization of a chain of spheres, conditional cores, contours-sensors of magnetic flux, magnetic induction and permeability

• **Submitted:** 23.03.2021 • **Revised:** 30.03.2021 • **Accepted:** 25.05.2021

For citation: Sandulyak A.A., Sandulyak D.A., Gorpinenko Y.O., Ershova V.A., Sandulyak A.V. Towards a model of chain-by-chain magnetization of a granular medium: a variant of magnetic diagnostics of chains of spheres. *Russ. Technol. J.* 2021;9(5):36–44. https://doi.org/10.32362/2500-316X-2021-9-5-36-44

Financial disclosure: The authors have no a financial or property interest in any material or method mentioned.

The authors declare no conflicts of interest.

НАУЧНАЯ СТАТЬЯ

К модели поцепочного намагничивания гранулированной среды: вариант магнитной диагностики цепочек шаров

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Резюме. Кроме информации о магнитных параметрах неоднородных, в частности гранулированных, магнетиков, обычно изучаемых в рамках модели квазисплошной среды, не меньший интерес представляет получение информации с позиций модели, когда объект изучения – характерные элементы неоднородного магнетика. Согласно хорошо зарекомендовавшей себя модели избирательного намагничивания гранулированной среды такими элементами, из которых состоит эта среда, являются цепочки гранул – прямые и извилистые, всегда проявляющие себя в направлении ее намагничивания. Они выполняют функцию проводников-каналов генерируемого магнитного потока сквозь гранулированную среду, вследствие чего она представляет собой своеобразный разветвленный «жгут» проводников-каналов. Для любой же из цепочек гранул, например, гранул-шаров радиусом R концептуально значимыми являются магнитные параметры ее условных сердцевин радиусом $r \leqslant R$. Эти параметры, прежде всего, магнитная проницаемость квазисплошных сердцевин и магнитная индукция в них, для разных (по r) сердцевин вариабельны, что требует соответствующей магнитной диагностики. Для выяснения магнитных параметров условных сердцевин цепочки гранул-шаров как физически самодостаточного элемента гранулированной среды (т.е. в соответствии с моделью поцепочного намагничивания такой среды), измерительные датчики магнитного потока в сердцевине практично выполнять в виде круговых датчиков, окружающих точку контакта гранул-шаров, но не традиционных петель из провода, а контуров на тонких печатных платах с посадочными отверстиями, помещаемых между смежными шарами. На основании полученных данных магнитного потока в разных по радиусу r сердцевинах (r/R = 0.2–0.9) цепочки шаров радиусом R = 20 мм определены значения магнитной индукции B в них, а также их магнитной проницаемости μ при намагничивании цепочки в соленоиде полем напряженностью от 4.8 до 54.5 кА/м. Показано, что при формальном утолщении сердцевин значения B и μ снижаются ввиду уменьшения объема ферромагнетика в сердцевине, а для предельной сердцевины ($r/R \to 1$), т.е. для цепочки в целом они ожидаемо соответствуют значениям B и μ для полишаровой среды-засыпки.

Ключевые слова: намагничивание цепочки шаров, условные сердцевины, контуры-датчики магнитного потока, магнитная индукция и проницаемость

• **Поступила:** 23.03.2021 • **Доработана:** 30.03.2021 • **Принята к опубликованию:** 25.05.2021

Для цитирования: Сандуляк А.А., Сандуляк Д.А., Горпиненко Ю.О., Ершова В.А., Сандуляк А.В. К модели по-цепочного намагничивания гранулированной среды: вариант магнитной диагностики цепочек шаров. *Russ. Technol. J.* 2021;9(5):36–44. https://doi.org/10.32362/2500-316X-2021-9-5-36-44

Прозрачность финансовой деятельности: Никто из авторов не имеет финансовой заинтересованности в представленных материалах или методах.

Авторы заявляют об отсутствии конфликта интересов.

INTRODUCTION: TO THE ROLE OF CHAINS OF GRANULES IN THE MAGNETIZATION OF A GRANULAR MEDIUM

The problem of investigation of the magnetic properties of various heterogeneous magnets, in particular, composites, suspensions, powders, granular packings, etc. [1–13], is typically considered to be more complex than the conventional problem of study of the magnetic properties of homogeneous (continuous) magnets. However, in most instances, the former problem is reduced to the determination of the same magnetic characteristics as those of continuous magnets. In this case, the magnetic parameters of an essentially quasi-continuous magnet being explored are often referred to as effective parameters.

Along with such information, i.e., that obtained from the standpoint of this macromodel as characterizing one or another heterogeneous magnet as a whole, it is important to obtain information on its “local” magnetic parameters from the point of view of a sort of a micromodel. And the preferred objects of investigation should be characteristic elements, including composite ones, of a heterogeneous medium of one or another type the micromodel magnetic parameters of which enable one to directly arrive at the macromodel magnetic parameters of the entire heterogeneous magnet.

In particular, such a solution was implemented for quite a widely used type of heterogeneous magnets—granular medium [13–16]. An original model of selective magnetization of a granular medium was used to show that a crucial role in the magnetization is played by such elements of the granular medium as chains of granules, straight and sinuous, which always respond in the direction of the magnetization of this medium. They act as channels that conduct the generated magnetic flux, and the crucial role of these constituent elements of the granular medium, which functions as a bundle of conducting channels, is suggested by the similarity of the field dependences of the magnetic flux density of an individual chain of granules and the entire granular medium [13–16].

DEVELOPMENT OF THE APPROACH TO MAGNETIC DIAGNOSTICS OF A CHAIN OF SPHERICAL GRANULES (BALLS)

According to the discussed model [13–16], for any chain of granules, e.g., spherical granules (balls) of radius R, conceptually significant are the magnetic parameters of their conditional cores of radius $r \leq R$, of course, as quasi-continuous magnets. Such parameters, first of all, their magnetic permeability and magnetic flux density at different core radii r are variable because of the difference in magnetic reluctance, which is due to the difference in volume of the gap between the surfaces of the neighboring granules and, consequently, the difference in metal volume in the cores. For the limiting core ($r \to R$), these parameters are virtually equal to those of the entire granular medium, which suggests the existence of expected relationships between the micromodel and macromodel parameters.

The variability of the magnetic parameters of different cores in a chain of balls was demonstrated by both calculations, and direct magnetic diagnostics of the field within the wedgelike space between balls of a chosen chain of balls [13–16]. Such diagnostics is known to be quite difficult to perform in small spaces; therefore, an efficient variant of it is to measure the magnetic fluxes (microfluxes) Φ through microwebermeter-connected concentric circular loops of different radii $r \leq R$, surrounding the point of contact of balls. Such loop sensors are located between the neighboring balls in the middle part of the chain of balls being magnetized. Inserting the loop sensors in so small a space between the balls, which converges as the point of contact of the balls is approached, one can measure the magnetic fluxes Φ through the cores of even relatively small relative radius r/R, especially if the balls in the chosen chain have large radius R, and the loops are made of sufficiently thin wire.

This approach was improved [17, 18] to avoid difficulties in meeting requirements for such sensors, especially the ones that should be inserted between balls and, therefore, have to be made of very thin wire. For example, it is necessary to ensure a strictly circular shape of the sensor, concentricity in the case of using a system of sensors of different radii, and localization of the sensor or a system of sensors in the plane of symmetry of the interball space to prevent the possible displacement of their centers relative to the point of contact of the balls. As applied to the problem under consideration, in which chain of balls 1 (Fig. 1) is magnetized in, e.g., solenoid 2, these requirements are sufficiently completely satisfied by sensor 3, which is a thin flat printed circuit board with a conducting circular loop or a system of concentric loop sensors on it. Each of the loops has a small break to connect the free terminals to the microwebermeter.

The printed circuit board ensures the strict shape of the loop sensor or each of the loop sensors in a system, namely, a geometrically perfect circle on a flat surface. It also (easily) ensures the localization of the loop sensor or a system of the concentric loop sensors in the plane of symmetry of the space between the balls being magnetized, in which such a printed circuit board is placed without fear for the possible displacement of the center of the loop or the system of the loops relative to the point of contact of the balls. For this purpose, there is a hole at the center of the printed circuit board, which is concentric to the loop sensor or the system of the loop sensors. As follows from the corresponding geometric constraints [17, 18], depending on the radius R of the chosen balls and the thickness δ of the thin printed circuit board, the seat diameter d_0 of the hole should be $d_0 = [\delta(4R - \delta)]^{0.5}$.

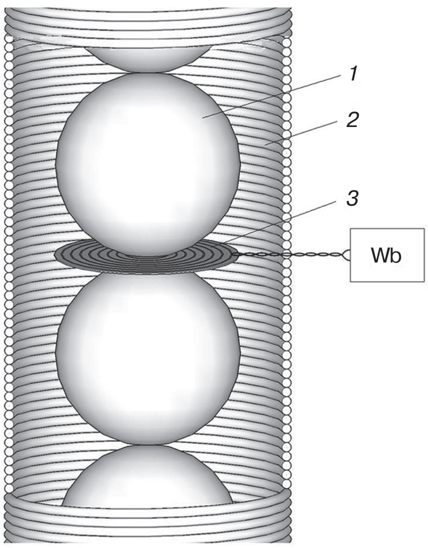

Fig. 1. Chain of balls *1* being magnetized in the field of solenoid *2* with microwebermeter-connected circular loop sensors *3* located on a thin printed circuit board placed between the balls

DATA ON THE MAGNETIC FLUX THROUGH THE CORES OF BALLS: MAGNETIC FLUX DENSITY AND PERMEABILITY

Figure 2a illustrates the results of measuring the magnetic microflux Φ through the loop sensors [17] and, hence, through the cores of the corresponding radius r of balls of a radius of R = 20 mm in a chain as a family of field dependences at various relative radii r/R. The data were obtained for quite a long chain of balls—14 ones—to minimize the demagnetization factor, the magnetizing field strength range was H = 4.8−54.5 kA/m, and the relative core radius range was r/R = 0.2−0.9.

Figure 2a shows that, with increasing H, Φ monotonically increases, and the higher H, the slower this increase, which is particularly noticeable at relatively small r/R. The larger the radius r of a core, the higher the magnetic flux Φ through it (Fig. 2a), which is more clearly demonstrated by a relative family of dependences of Φ on r/R at various H (Fig. 2b).

Using the experimental Φ values (Fig. 2), it is easy to find the magnetic flux density B through each of the quasi-continuous cores of radius r and sectional area πr^2 as $B = \Phi/\pi r^2$, and also the magnetic permeability μ of the corresponding cores as $\mu = B/\mu_0 H = \Phi/\pi r^2 \mu_0 H$, where $\mu_0 = 4\pi \cdot 10^{-7}$ H/m is the vacuum permeability. Figures 3 and 4 present the data on B and μ for the cores of different r/R as families of dependences of B and μ on H, respectively; from these dependences, families of no less informative dependences of B and μ on r/R (at different H) were obtained and are also shown in Figs. 3 and 4, respectively.

Figure 3a shows that, with increasing magnetic field strength H, the magnetic flux density B through each of the cores monotonically increases, but the higher H, the less intense this increase (as for Φ in Fig. 2a), which is best seen at small r/R. The larger the core radius r, the lower the magnetic flux density B through it (Fig. 3a): this is better observed in the dependences of B on r/R at various H (Fig. 3b).

The magnetic permeability μ of the corresponding (in r/R) cores decreases with increasing H (Fig. 4a). As for B (Fig. 3), the larger the radius r of a core, the lower its permeability μ (Fig. 4). This can be seen already from the relative positions of the curves of the dependences of μ on H (Fig. 4a), and also from the decreasing trends of the dependences of μ on r/R at various H (Fig. 4b), which were obtained from the dependences in Fig. 4a.

The observed (Figs. 3, 4) decrease in B and μ with increasing radius r of conditional cores (the relative radius r/R of which ranges from $r/R \to 0$ to $r/R = 1$) is caused by the decrease in the volume fraction γ of the ferromagnetic metal in the growing core. For example, using the relationship between γ and r/R [17]:

$$\gamma = \frac{2}{3}\left[\sqrt{1-(r/R)^2} + \frac{1-\sqrt{1-(r/R)^2}}{(r/R)^2}\right], \tag{1}$$

the key parameters, namely the magnetic flux density B and the magnetic permeability μ, which are presented in

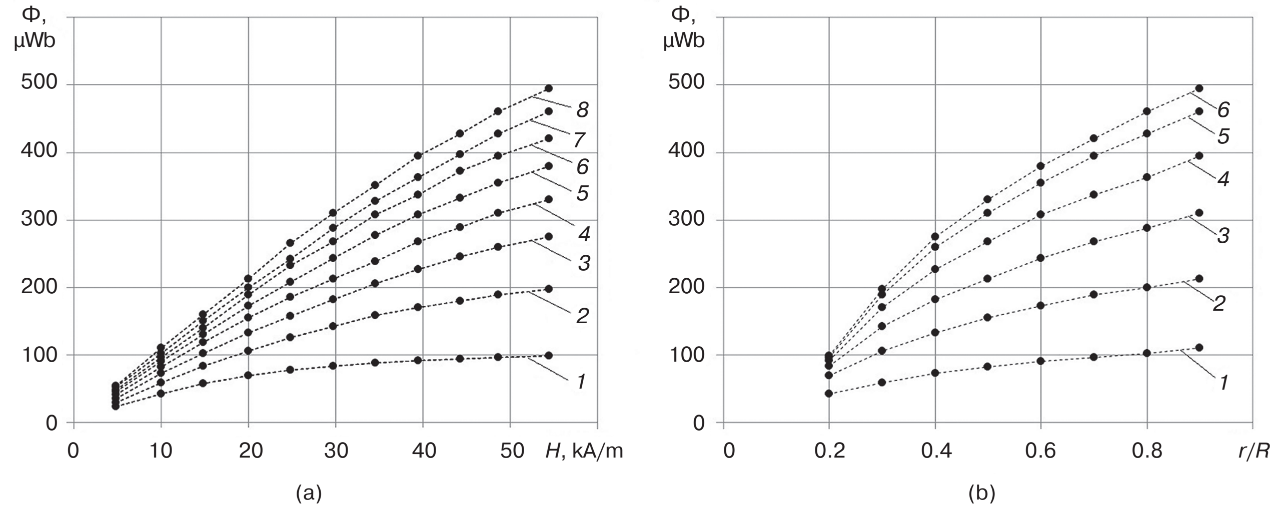

Fig. 2. Dependences of the magnetic microflux Φ through the loop sensors surrounding the cores of radius r of balls of a radius of R = 20 mm in a chain on (a) the magnetic field strength H at r/R = (*1*) 0.2, (*2*) 0.3, (*3*) 0.4, (*4*) 0.5, (*5*) 0.6, (*6*) 0.7, (*7*) 0.8, and (*8*) 0.9 and (b) on the relative core radius r/R at H = (*1*) 10, (*2*) 20, (*3*) 29.7, (*4*) 39.5, (*5*) 48.7, and (*6*) 54.5 kA/m

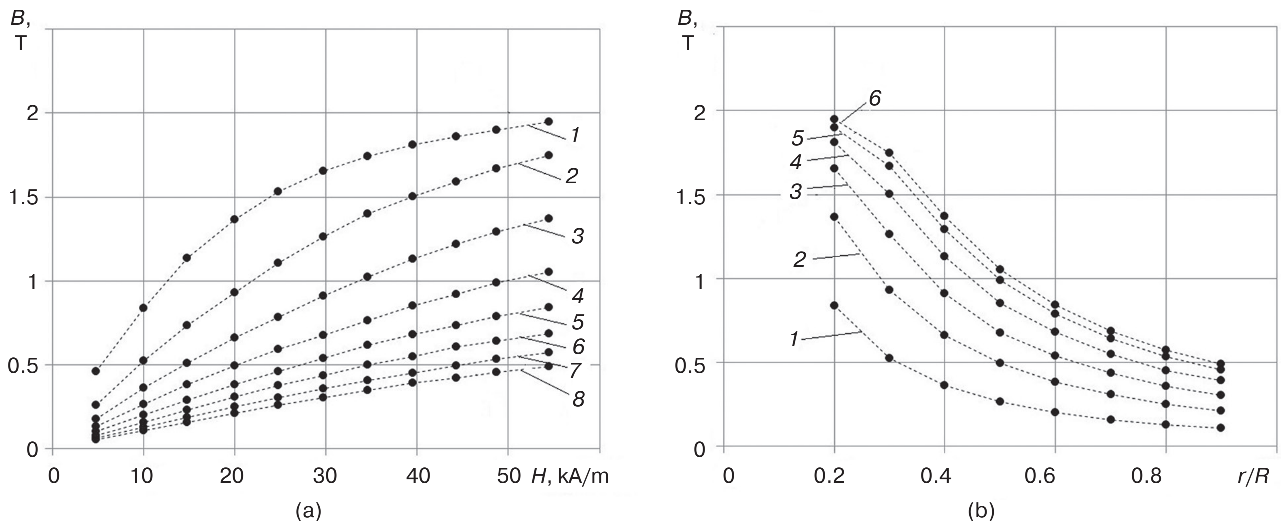

Fig. 3. Dependences of the magnetic flux density B in the cores of balls of a chain on (a) the magnetic field strength H and (b) the relative core radius r/R. The notation is as in Fig. 2

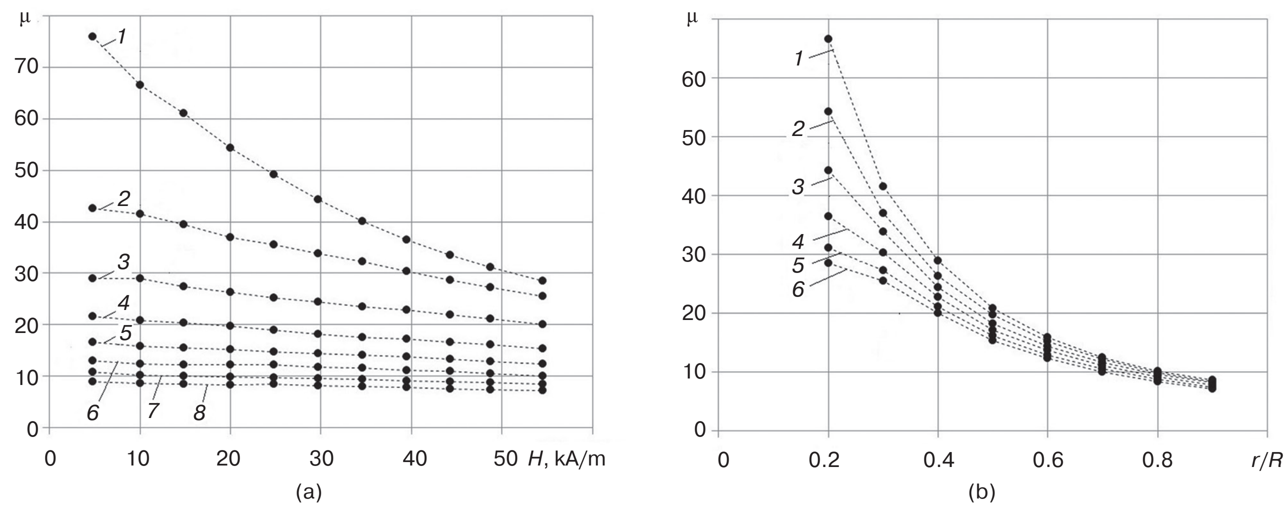

Fig. 4. Dependences of the magnetic permeability μ of the cores of balls of a chain on (a) the magnetic field strength H and (b) the relative core radius r/R. The notation is as in Fig. 2

Figs. 3b and 4b, respectively, as functions of r/R, can be represented as functions of γ (Fig. 5) to demonstrate the role of such a hidden parameter as volume fraction γ of metal in the cores of balls in a chain.

An analysis of these, quite informative, trends of the dependences of B and μ on γ in Fig. 5 toward increasing γ shows that the role of γ is particularly significant at γ = 0.9–0.95, i.e., as $\gamma \to 1$ (and, correspondingly, $r/R \to 0$). Here, the increase in B and μ is definitely steep, and these quantities tend to approach the B and μ values that are characteristic of the material of the balls. No less informative are the trends of the dependences of B and μ on γ in Fig. 5 toward decreasing γ, down to the values $\gamma \to 0.67$ (i.e., $r/R \to 1$), which are characteristic of the chain of balls. This allows one to test the validity of the conceptual assumption of the magnetization model that the magnetic properties of a chain of balls and a ball-packed medium should be similar. In particular, this can be tested by comparing the field dependences of B and/or μ in the chain and the packing.

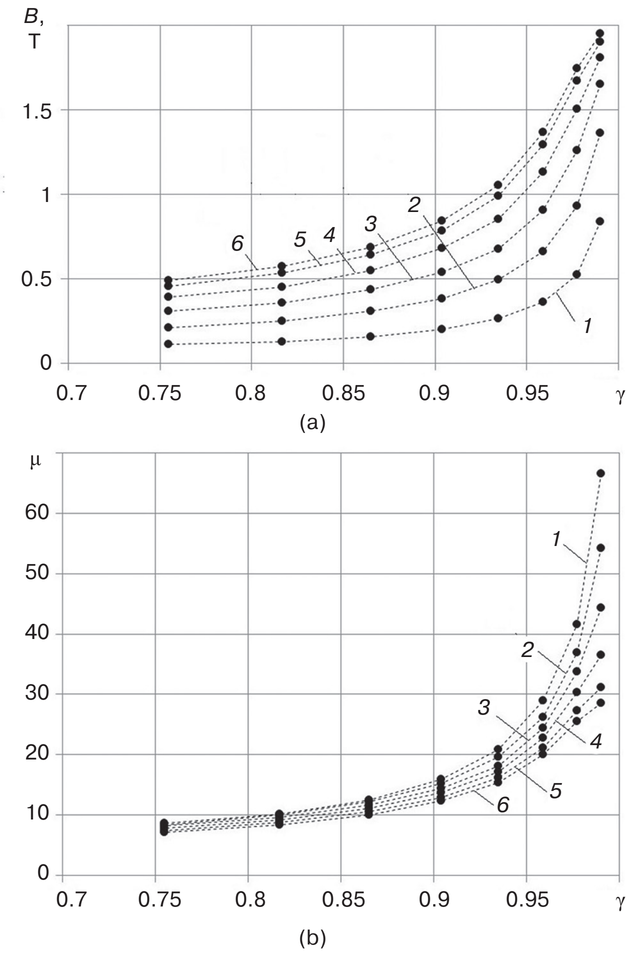

Fig. 5. Dependences demonstrating the effect of the volume fraction γ of metal in the conditionally separated, different in radius r, cores of balls in a chain on (a) the magnetic flux density B in them and (b) their magnetic permeability μ according to the data in Figs. 3 and 4 using relationship (*1*) between γ and r/R

The field dependences of the magnetic flux density B and permeability μ for a chain of balls can be obtained using the data in Fig. 5. In the experiments [17], the maximum relative radius of loop sensor (and their surrounding conditional cores of balls in a chain) was r/R = 0.9 (i.e., γ = 0.755 in Fig. 5); nonetheless, a reliable estimate of the B and μ values up to the required value r/R = 1, i.e., to γ = 0.67, is easy to make. The trends of the dependences of B and μ on γ toward decreasing γ, being near-self-similar at $\gamma < 0.755$ (or, what is the same, at $r/R > 0.9$) (Fig. 5), can readily be extrapolated to the left to $\gamma = 0.67$, i.e., to $r/R = 1$. It is easy to see that the differences of then extrapolated values of B and μ from the B and μ values at γ = 0.755 (i.e., at r/R = 0.9) are quite insignificant (Fig. 5).

This makes it possible to represent the field dependences of the magnetic flux density B and permeability μ for a chain of balls (Fig. 6, curves *1*) using the extended data: at γ = 0.755–0.67 (i.e., at r/R = 0.9–1.0). For the above-proposed comparison, Fig. 6 also presents the published [13] field dependences of B and μ for a ball-packed medium (curves *2*). One can see that, to within virtually a constant, the compared field dependences of both the magnetic flux density B (Fig. 6a, curves *1*, *2*), and the permeability μ (Fig. 6b, curves *1*, *2*) agree with each other. This confirms that a chain of granules is a physically self-sufficient element (in the composition of a bundle of similar elements) of a granular medium, which is actually responsible for the magnetization of this medium.

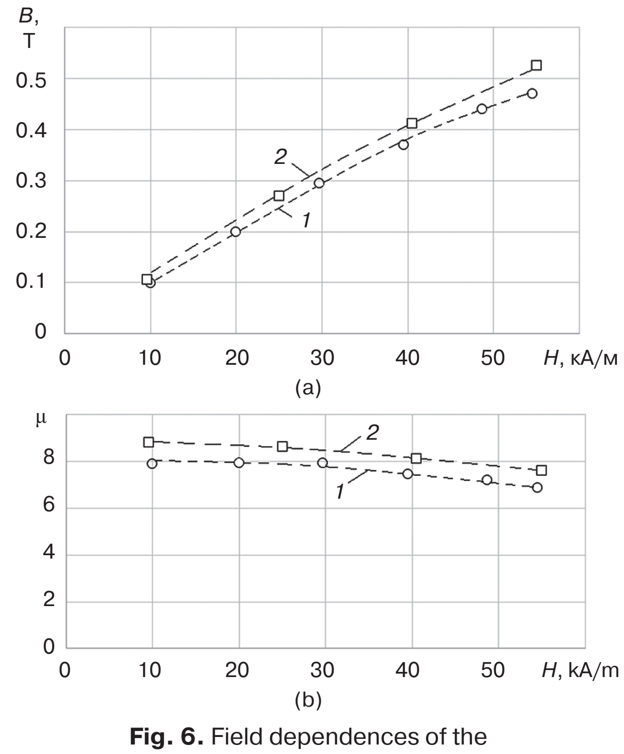

Fig. 6. Field dependences of the (a) magnetic flux density B and (b) permeability μ of (*1*) a chain of balls (its virtually limiting core at r/R = 0.9–1.0) and (*2*) a ball-packed medium

CONCLUSIONS

One of the concepts of the well-proven model of chain-by-chain magnetization of a granular medium is the crucial role of such constituting elements of the granular medium as chains of granules, straight and sinuous, which always respond in the direction of the magnetization of this medium. They function as channels that conduct the generated magnetic flux; i.e., the granular medium is a sort of a bundle of these elements. Conceptually significant are the magnetic parameters of the conditional cores of different radii r of granules in a chain, first of all, their magnetic permeability and magnetic flux density. These parameters can be determined from the results of measurements made by magnetic flux sensors designed as concentric circular conducting loops of different radii $r \leq R$, surrounding the point of contact of the balls, that are produced on thin printed circuit boards placed in the plane of symmetry of the space between the contacting balls. The analysis was made of the results of measuring the magnetic fluxes through different (in relative radius $r/R = 0.2–0.9$) cores of balls of a radius of $R = 20$ mm in a chain at a magnetizing field strength in the range 4.8–54.5 kA/m. It was shown that, with formally thickening cores, the values of the magnetic flux density and the permeability decrease because of the decrease in the volume fraction of ferromagnet in the core; and in the limiting core ($r/R \to 1$), i.e., the entire chain, they agree with the values of the magnetic flux density and the permeability of the ball-packed medium. This confirms the corresponding results of the model of chain-by-chain magnetization of a granular medium.

Acknowledgments. This research was supported by the Ministry of Science and Higher Education of the Russian Federation (project 0706-2020-0024) and the program of the President of the Russian Federation for state support of young scientists (project MK-807.2020.8).

Authors' contribution. All authors equally contributed to the research work.

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Translated by V. Glyanchenko