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Prospects for the Development of Smart Clothing with the Use of Textile Materials with Magnetic Properties

Možnosti za razvoj pametnih oblačil z uporabo tekstilnih materialov z magnetnimi lastnostmi

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Abstract

The article studies the properties of textile materials filled with magnetite nanoparticles. These materials have great prospects for creating smart clothes. They have both magnetic and hygienic properties. Chemical transformations in the production of magnetic nanopowder are described. The end product of the process is a mixture of oxides of divalent and ferric iron. The resulting mixture has magnetic properties. Conducted micro and macro experiments showed sufficient adhesion retention strength of magnetite nanoparticles in a textile material. Microscopic studies of the attachment of magnetic particles to the fibers of a textile material have been conducted. The data obtained in express mode allow us to determine the average mass of a magnetic particle in a textile material, the total number of nanoparticles, and, accordingly, to predict the magnetic force that a textile material saturated with magnetite can possess. The existence of the magnetic properties of a textile material filled with magnetite nanoparticles has been proven. A mathematical model of the dependence of the magnetic attraction force of a textile material on the distance and the number of abrasion cycles has been developed. The directions of the use of magnetic textile materials for the creation of smart clothes are proposed. Potential uses for such materials include sportswear and textiles for the disabled. The developed methods can predict the magnetic strength of the obtained textile materials and evaluate their resistance, which is necessary in the development of smart clothing elements based on these materials.
Keywords: textile materials, nanotechnology, magnetite, smart clothes, magnetic force

Izvleček

Članek je posvečen študiji lastnosti tekstilnih materialov, funkcionaliziranih z nanodelci magnetita, ki izkazujejo velik potencial za izdelavo pametnih oblačil. Odlikujejo jih magnetne in higienske lastnosti. Opisane so kemične pretvorbe pri proizvodnji nanodelcev magnetita v prahasti obliki. Končni produkt postopka je zmes oksidov dvovalentnega in trivalentnega železa. Nastala zmes ima magnetne lastnosti. Rezultati izvedenih analiznih metod so pokazali zadostno adhezijo magnetitnih nanodelcev v tekstilnem materialu. Opravljena je bila mikroskopska analiza magnetnih delcev na vlaknih tekstilnega materiala. Pridobljeni podatki omogočajo določitev povprečne mase magnetnih delcev v tekstilnem materialu, skupnega števila nanodelcev in posledično napoved magnetne sile, ki jo lahko ima tekstilni material, funkcionaliziran z magnetitom. Dokazan je bil obstoj magnetnih lastnosti funkcionaliziranega tekstilnega

materiala. Razvit je bil matematični model odvisnosti magnetne privlačne sile tekstilnega materiala od razdalje in števila ciklov drgnjenja. Predlagane so usmeritve za uporabo magnetnih tekstilnih materialov za izdelavo pametnih oblačil. Potencialne uporabe takšnih materialov so športna oblačila in tekstil za invalide. Z razvitimi metodami lahko predvidimo magnetno moč proizvedenih tekstilnih materialov in ocenimo njihovo obstojnost, kar je potrebno pri razvoju pametnih oblačil, ki temeljijo na teh materialih.
Ključne besede: tekstilni material, nanotehnologija, magnetit, pametna oblačila, magnetna sila

1 Introduction

The trend of developing and creating smart clothes and smart materials is quite pronounced across the world. In some cases, the development of such clothing is based on traditional textile materials. At the same time, materials with new properties that allow you to create clothes of a new level constantly appear in the world. In [1], fabrics with the properties of electrical conductivity are considered, and in [2], materials with controlled thermal conductivity are developed.
In many cases, the creation of new textile smart materials is associated with modern nanotechnology. Articles [3, 4] substantiate the active development of textile materials using innovative nanotechnologies both in the production of such materials and in the direction of their finishing.
A large place is occupied by metal nanoparticles, which give the materials various properties in the process of creating textile materials with new properties. In [5], zinc oxide nanoparticles were proposed to be used as chemical protective materials, while the efficiency was recognized as being quite high during photocatalytic degradation.
The article [6] states that homogeneous nanoparticles of TiO_2 and SiO_2 can be useful for developing methods of protection against ultraviolet radiation for various substrates, including textile ones.
One of the applications of such materials is to protect against ultraviolet radiation, which has a negative effect on the human body [7]. The work [8] shows the process of metallizing textile materials with metal nanoparticles in order to protect a person from electromagnetic radiation.
A series of data indicates that the filling of textile materials with nanoparticles has a significant antimicrobial effect. According to various data, such an effect can be exerted by silver and copper nanoparticles upon their modification of textile fibers [9]. Also, the results on the deposition of zinc dioxide nanoparticles for antimicrobial finishing of cotton fabric [10] are known.
The article [11] shows the use of metallic nanomaterials in imparting antimicrobial properties to textiles. Adhesive and protective properties were investigated. The test results showed that the nanoparticle coated fibers had high antibacterial activity.
A number of studies consider the use of magnetite nanoparticles [12], which in addition to magnetic and protective properties, also have bacteriostatic properties [13] as a prospect.
The introduction of such materials into modern smart technologies is hampered by the absence of regularities in their properties, which, in turn, is constrained by the complexity of micro-researching nanomaterials. In [14–15], express methods for studying nanomaterials based on mathematical modeling of their dispersion are substantiated.
The aim of this work is to substantiate the laws of magnetic properties in textile materials containing magnetite nanoparticles based on statistical micrometric studies through the process of modeling the real magnetite content in textile fibers.
The obtained results will allow us to develop smart materials with new qualities, which, in addition to the properties of antimicrobial and electromagnetic protection, will have magnetic qualities which will significantly expand the scope of their application [16–17].

2 Methodology

The device is based on a glass reactor for the synthesis of substances 1 (Figure 1). Above the reactor (1) filled with solution (2), an asynchronous motor (4) is fixed and a glass mixer (3) is connected to it. Given the low mechanical properties of the mixer and the need to prevent unwanted vibrations, the mixer passes through an additional bearing (5). The speed of the motor is regulated by a transformer.
The process is carried out in a chemical cabinet with the suction of unwanted substances. Aqueous mixtures of ferrous sulfate and ferric chloride are mixed in the reactor.

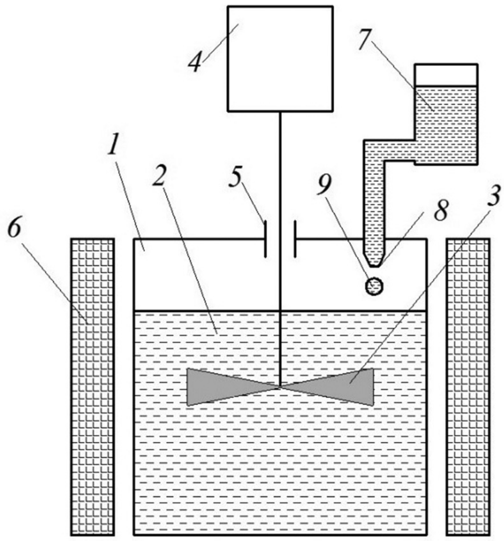

Figure 1: Device for mixing the solution for the preparation of magnetite
Legend: 1 – reactor 2 – solution 3 – glass mixer 4 – asynchronous motor 5 – bearing 6 – thermal insulator 7 – solution of ammonia 8 – dispenser 9 – drops of ammonia

The reactor is covered by a thermal insulator. Above the reactor, a vessel with a solution of ammonia (7) is situated. Through the dispenser (8), the liquid is fed in drops (9) into the reactor hole.
Continuous stirring is performed. Samples are constantly taken until an alkaline environment is achieved.
The reactions that occur can be represented as:

$$FeSO_4 + 2\ NH_4OH \rightarrow FeO + (NH_4)_2SO_4 \quad (I)$$

$$FeCl_3 + NH_4OH \rightarrow Fe(OH)_3 + (NH_4)_3Cl \quad (II)$$

$$2\ Fe(OH)_3 \rightarrow Fe_2O_3 + H_2O \quad (III).$$

The finished product of our process is a mixture of oxides of ferrous and trivalent iron. The resulting mixture has magnetic properties. Raising a magnet to the vessel forms a characteristic profile of the location of the particles (Figure 2). The most probable reason for the curvature of the distribution profile is the different particle size. According to our hypothesis, the deviation of the profile from the line shows the deviation of particle sizes from the mean value. The resulting distribution is almost normal.
The final product was obtained using a device for vacuum filtration (Figure 3). This device consisted of a vacuum pump (1), a Bunsen flask (2) and a Buchner funnel (3).

Figure 2: Demonstration of magnetic properties of magnetite nanoparticles

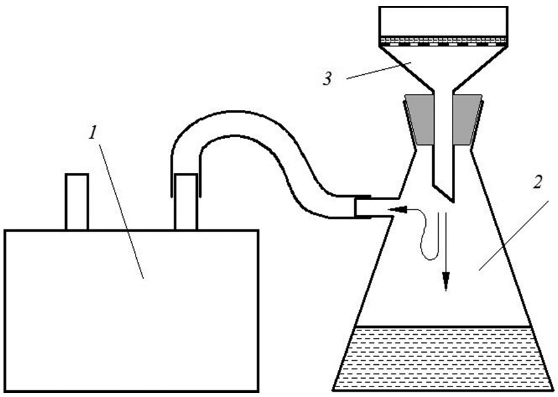

Figure 3: Device for vacuum filtration of magnetite
Legend: 1 – vacuum pump 2 – Bunsen flask 3 – Buchner funnel

Magnetite was applied to the fabric surface as a suspension of nano powder with a Fe_3O_4 content of 43% stabilized potassium oleate. After application to the material, the samples were squeezed, rinsed in cold water and dried. The strength of the nanopowder in the fibers of the material was checked by conducting abrasion tests of the samples and microscopic studies of the microfibers of the material were conducted.

3 Results and discussion

Magnetite impregnation of cotton textile material results in the appearance of magnetic properties.
Micrometric studies of cotton fibers impregnated with magnetite nanoparticles demonstrate a rath-

er complex distribution of particles over the fibers (Figure 2). At the same time, significant adhesion of particles to fibers is observed. Unfortunately, an optical microscope under the conditions of rapid experiments does not make it possible to identify magnetite particles in the nanoscale range.

At the same time, these conditions make it possible to identify the initial branch of the particle size distribution curve. Based on the assumptions given in [15], the distribution of the dimensions of magnetic particles can be described by the equation 1 and a graph, shown in Figure 3:

$$f(d) = \frac{\alpha}{\beta^{\alpha}} d^{\alpha-1} e^{-\left(\frac{d}{\beta}\right)^{\alpha}} \quad (1),$$

where d is the dimension of a magnetic particle, a and b are constants that show the dispersion intensity of nanoparticles.

In this case, the difference between Smik and Smax shows the area available for observation in an optical microscope. The obtained data in the microsize range (Figure 2) allow the prediction of the size distribution according to the method described in the article [15].

The data obtained in express mode allow us to determine the average mass of a magnetic particle in a textile material, the total number of nanoparticles, and, accordingly, to predict the magnetic force that a textile material saturated with magnetite can possess. Unfortunately, most of the magnetite particles deposited on the textile material have nanoscale and are not available for direct observation. Meanwhile, the technique described in [15] makes it possible to determine the real distribution based on the analysis of measurements in the optical range. In this case, the proportion of nanoparticles that fall into different size ranges, determined by the method of [15] is given in Table 1.

To reveal the magnetic properties of the obtained textile materials, an installation was used (Figure 4), in which a sample with a magnetic textile material (1) is located. The instrument is based on an electronic balance (2). The sample (1) is separated from the balance

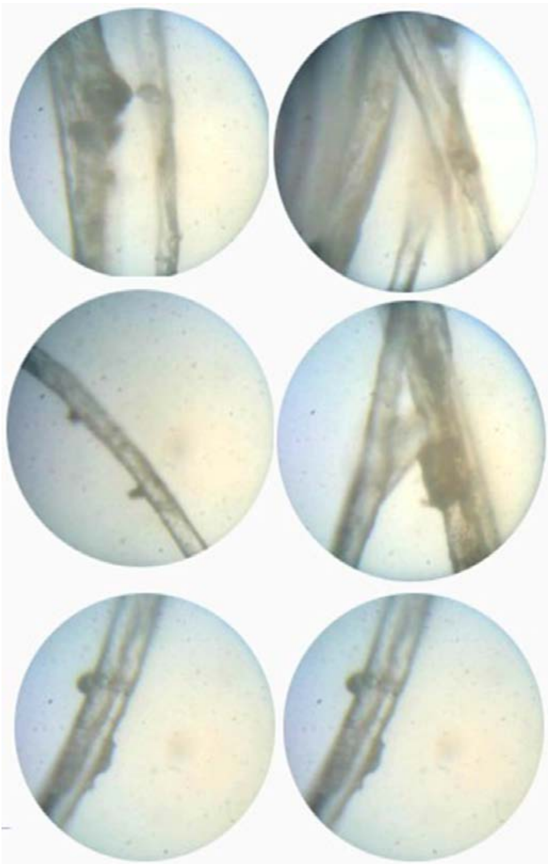

Figure 4: Cotton fabric fibers with magnetite microparticles

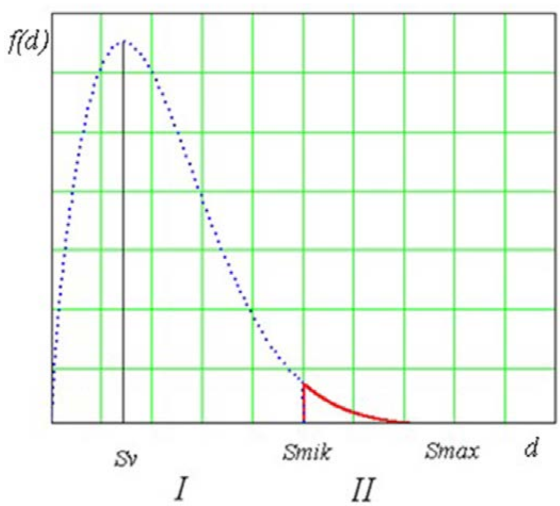

Figure 5: The distribution of magnetite particles on the fibers of a textile material

Table 1: Particle size distribution

Particle size (nm)	0–30	30–60	60–90	90–120	120–150	150–180
Relative number	0.18	0.26	0.21	0.15	0.1	0.04

using a magnetic insulator (3) to prevent the influence of magnetic fields on the balance readings. A permanent magnet (4) is fixed on the rack (5) above the balance. This device has the ability to change the distance between the magnet and the material *x*. The difference between the readings of the balance in a magnetic field and without it shows the magnetic force that acts on the textile material.

For the experiment, a sample of cotton material was taken with a surface density of 60–90 g/m^2 with a size of 10 × 10 cm (Figure 6).

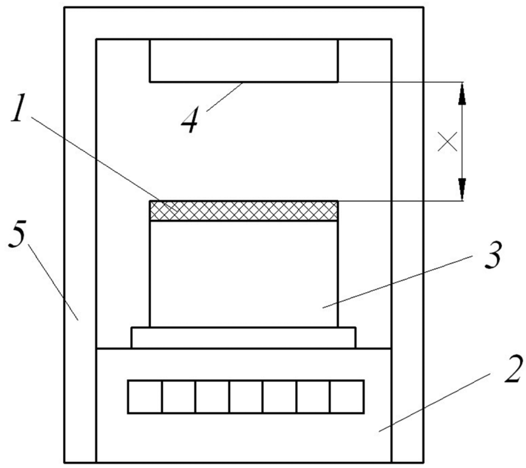

Figure 6: Measuring the force of magnetic attraction

Legend: 1 – textile material 2 – electronic balance 3 – magnetic insulator 4 – permanent magnet 5 – rack

Experiments with different saturations of textile material with magnetite nanoparticles were conducted. The distance from the magnet, as well as the content of nanoparticles in the material were changed. In addition, the retention resistance of the nanoparticles in the textile material was measured. In this case, the material with deposited magnetite was subjected to cyclic abrasion, after which the magnetic attraction force was measured.

Let us analyze the graph in Figure 7. When the magnet is removed from the material, the graph asymptotically approaches zero. The exponential function (equation 2)

$$f(x) = a \cdot e^{-b\left(\frac{h-x}{h}\right)} \tag{2}$$

where *a* is the force corresponding to the weight of the sample, *b* is the intensity of the decrease in force with distance from the magnet, *h* is the distance to the magnet at which the force of attraction corresponds to the weight of the sample.

In this function, the value of h determines the distance to the magnet at which the force of attraction corresponds to the weight of the sample (the material ceases to be a separate sample and sticks to the magnet), the value of b determines the intensity of the decrease, the value of a determines the value of the function. The value of h below the exponent in the denominator is entered to ensure that the argument is dimensionless.

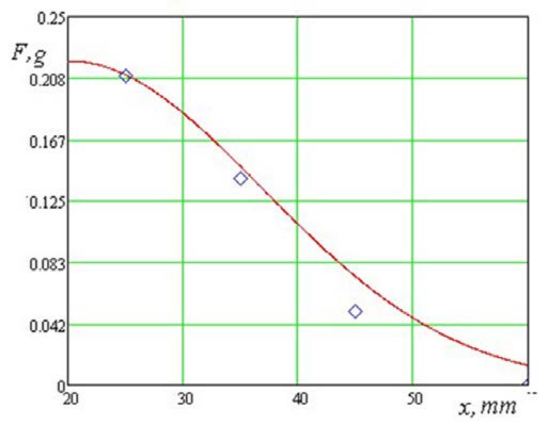

Figure 7: Changing the magnetic force of a textile sample from a distance

At zero value of x-h, the maximum force of attraction of the textile material to the magnet is observed. The behavior of the function demonstrates the extremum. Such behavior cannot be described by a simple exponent. To ensure this behavior, it is proposed to exponentiate the argument below the exponent. Then, the function will take the form of equation 3.

$$F = a \cdot e^{-b\left(\frac{x-h}{h}\right)^2} \tag{3}$$

where *F* is force of attraction of textile material to the magnet.

To check the existence of an extremum, you can determine the derivative (equation 4).

$$\frac{dF}{dx} = -2 \cdot a \cdot b \frac{x-h}{h^2} e^{-b\left(\frac{x-h}{h}\right)^2} \tag{4}$$

This derivative is zero for x = h. This corresponds to the condition of Figure 7.

The conducted studies of the magnetic properties showed the dependence on the saturation of the tissue with magnetite particles, the distance to the magnet, the number of cycles of friction between the tissue and the nanoparticles. The measurement results are shown in Figure 4.
The data in Figure 2 can be approximated by dependence (equation 4).

$$F = 0{,}23 \cdot e^{-0{,}74\left(\frac{x-20}{20}\right)^2} \quad (4)$$

Tests were carried out with the abrasion of a textile sample after ten, thirty and one hundred abrasions. It was shown that in the general case the magnetic force is determined by equation 5.

$$F = a \cdot e^{-b\left(\frac{x-20}{20}\right)^2} \quad (5)$$

The values included in this expression can be found from the experimental dependences in Figure 5.

As a result, the dependence of the magnetic force on the number of abrasions can be determined by the expression (6).

$$F = 0{,}115 \cdot \left(1 + e^{-\frac{n}{30}}\right) \cdot e^{-\left[0{,}74+0{,}19\cdot\left(1-e^{-\frac{n}{25}}\right)\right]\left(\frac{x-20}{20}\right)^2} \quad (6)$$

This value of the force of attraction to the magnet can be used in the process of designing special clothing.

In previous publications [16], we proved the bacteriostatic properties of textile materials filled with nanoparticles. In this work [18], directions for creating smart clothes based on metamaterials are proposed. The existing proposals for the development of smart clothes [19] do not provide for the active influence of clothes on a person. The use of magnetic textile materials based on magnetite nanoparticles makes it possible to create smart clothes with active action.

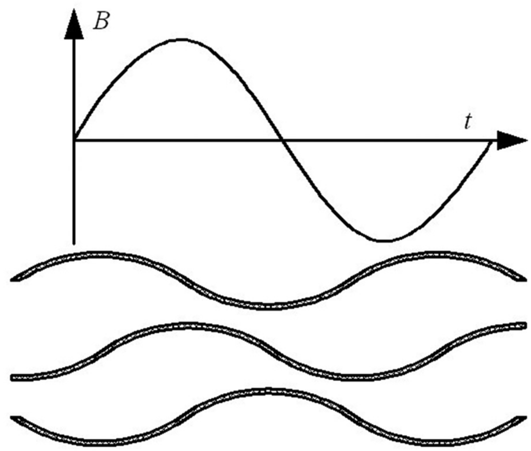

Figure 9: Movement of a magnetic textile material in an alternating magnetic field

In the case of an alternating magnetic field, the magnetic textile material acquires the ability to move in a controlled manner (Figure 9). This dynamic allows for a massaging or other movement to provide comfort, which can be beneficial for athletes [20] or sick people. Application of magnetic nanomaterials to the surface of pile materials are shown in Figure 10.

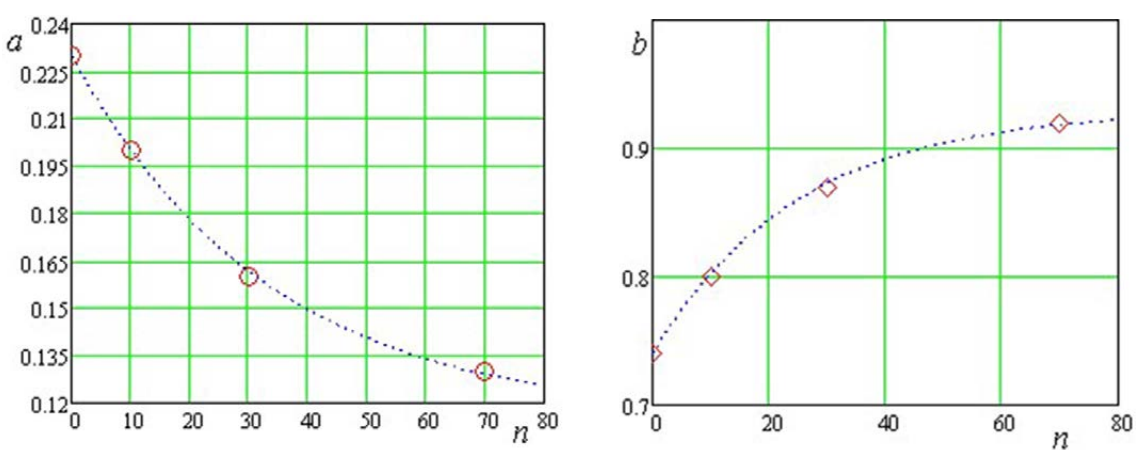

Figure 8: Parameter "a" and "b" change based on the number of abrasions

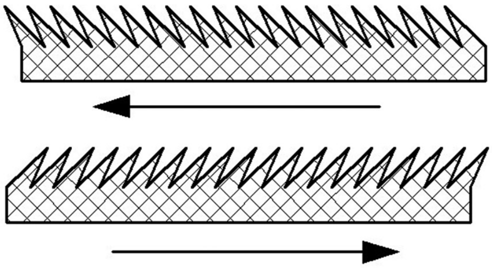

Figure 10: Magnetic pile materials in an alternating magnetic field

In the case of using pile magnetic materials, it becomes possible to localize the body in an arbitrary place to create a treatment effect or comfort.

4 Conclusion

Textile material filled with nanoparticles of magnetite has great prospects for creating smart clothes. The resulting materials, in addition to magnetic properties, have a hygienic and disinfecting effect. A mixture of oxides of ferrous and ferric iron in the form of nanoparticles has good adhesion to the fibers of the textile material. An express method for predicting the statistical distribution of magnetite nanoparticles in a textile material based on observation data is proposed. The developed methods can predict the magnetic strength of the obtained textile materials and evaluate their resistance, which is necessary when developing smart clothing elements based on these materials.

According to our observations, the mechanical properties of the textile material changed insignificantly after the application of magnetic nanopowder. The resistance to retention of magnetic nanoparticles increases significantly over time and after 2–3 days abrasion is almost not observed. We believe that the kinetics of changes in the retention resistance of nanoparticles in a textile material requires further study.

In addition, our preliminary studies described in [17] demonstrate the bacteriostatic properties of magnetic textiles, which will further prove the rationality of its use in smart clothing.

References

1. BARABÁŠ, J., BALOGOVÁ, Ľ., GÁLA, M., BABUŠIAK, B. Conductive paths and influence of theirinterconnection on tranmission of electric signal in smart clothing. *Vlákna a textil*, **24**(4), 2017, 9–14.
2. ROGALE FIRŠT, Snježana, ROGALE, Dubravko, NIKOLIĆ, Gojko Intelligent clothing: first and second generation clothing with adaptive thermal insulation properties. *Textile Research Journal,* 2018, 88(9), 2214–2233, doi: 10.1177/0040517517718190.
3. MAGNI, A. Nanotechnologies and the textile industry: the future is upon us. *Tinctoria*, 2004, **101**(10), 60–61.
4. YEZHOVA, O.V. Prognosing development of textile nanotechnologies. *Vlákna a textil*, 2017, **24**(4), 66–69.
5. HAN, Y., OBENDORF, S.K. Reactivity and reusability of immobilized zinc oxide nanoparticles in fibers on methyl parathion decontamination. *Textile Research Journal*, 2016, **86**(4), 339–349, doi: 10.1177/0040517515596935.
6. ZHANG, M., XIE, W., TANG, B., SUN, L., WANG, X. Synthesis of TiO_2&SiO_2 nanoparticles as efficient UV absorbers and their application on wool. *Textile Research Journal*, 2017, **87**(14), 1784–1792, doi: 10.1177/0040517516659375.
7. VLASENKO, V., SMERTENKO, P., BEREZNENKO, S., ARABULI, S. Synthesis of metals nano-particles in the porous structure of textiles for UV-shielding. *Vlákna a textil*, 2017, **24**(4), 30–33.
8. DIACHOK, T., BEREZNENKO, S., YAKYMCHUK, D., ALEKSANDROV, M. Development of equipment for complex man protection from artificial non-ionizing EMR. *Vlákna a textile*, 2019, **26**(2), 9–13.
9. GUTAROWSKA, B., STAWSKI, D., SKÓRA, J., HERCZYŃSKA, L., PIELECH-PRZYBYLSKA, K. PLA nonwovens modified with poly(dimethylaminoethyl methacrylate) as antimicrobial filter materials for workplaces. *Textile Research Journal*, 2015, **85**(10), 1083–1094, doi: 10.1177/0040517514559581.
10. KAR, T.R., SAMANTA, A.K., SAJID, M., KAWARE, R. UV protection and antimicrobial finish on cotton khadi fabric using a mixture of nanoparticles of zinc oxide and poly-hydroxy-amino methyl silicone. *Textile*

Research Journal, 2019, **89**(11), 2260–2278, doi: 10.1177/0040517518790973.

11. XU, S., ZHANG, F., SONG, J., KISHIMOTO, Y., MORIKAWA, H. Preparation of silver nanoparticle-coated calcium alginate fibers by hyperbranched poly(amidoamine)-mediated assembly and their antibacterial activity. *Textile Research Journal*, 2015, **86**(8), 878–886, doi: 10.1177/0040517515599745.
12. BOGREN, S., FORNARA, A., LUDWIG, F., DEL PUERTO MORALES, M., STEINHOFF, U., HANSEN, M.F., KAZAKOVA, O., JOHANSSON, C. Classification of magnetic nanoparticle systems - synthesis, standardization and analysis methods in the NanoMag project. *International Journal of Molecular Sciences*, 2015, **16**(9), 20308–20325, doi: 10.3390/ijms160920308.
13. TSYKHANOVSKA, I., YEVLASH, V., ALEXANDROV, A., KHAMITOVA, B., SVIDLO, K., NECHUIVITER, O. Forming the structure of whipped desserts when introducing the food additive "Magnetofood" to their formulation. *Eastern-European Journal of Enterprise Technologies,* 2019, **2**(11(98)), 45–55, doi:10.15587/1729-4061.2019.161855.
14. RODGERS, J., ZUMBA, J., FORTIER, C. Measurement comparison of cotton fiber micronaire and its components by portable near infrared spectroscopy instruments. *Textile Research Journal*, 2017, **87**(1), 57–69, doi: 10.1177/0040517515622153.
15. RIABCHYKOV, M., ALEXANDROV, A., TSYKHANOVSKA, I., NECHIPOR, S., NIKULINA, A., VILKOV, S. Distribution of the sizes of microcapsules in two-phase emulsions for treatment of textile materials. *Vlákna a textile*, 2019, **26**(4), 47–52.
16. LIU, S., TONG, J., YANG, C., LI, L. Smart e-textile: resistance properties of conductive knitted fabric - single pique. *Textile Research Journal*, 2017, **87**(14), 1669–1684, doi: 10.1177/0040517516658509.
17. RIABCHYKOV, M., ALEXANDROV, A., SYCHOV, Y., NIKULINA, A. Bacteriostatic properties of medical textiles treated with nanomaterials based on Fe_2O_3. *IOP Conference Series: Materials Science and Engineering,* 2021, **1031**(1), 1–6, doi:10.1088/1757-899x/1031/1/012036.
18. MORADI, B., FERNÁNDEZ-GARCÍA, R., GIL, I. Effect of smart textile metamaterials on electromagnetic performance for wireless body area network systems. *Textile Research Journal*, 2019, **89**(14), 2892–2899, doi: 10.1177/0040517518803786.
19. PÉREZ-VILLACASTÍN, Julián, GAETA, Eugenio. Smart clothes to take care of people or smart people who use clothes to take care of themselves? *Revista Española de Cardiología*, 2015, **68**(7), 559–561, doi: 10.1016/j.rec.2015.03.009.
20. SCATAGLINI, S., MOORHEAD, A.P., FELETTI, F. A systematic review of smart clothing in sports: possible applications to extreme sports. *Muscles, Ligaments and Tendons Journal*, 2020, **10**(2), 333–342.