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Magnetic Textile Elements

Abstract
This article presents the properties of magnetic fibres and the opportunities to use them in the construction of textile magnetic elements. Magnetic fibres belong to the group of multifunctional fibres, as independently of their natural textile features they are characterised by new properties which increase their range of possibilities for use in textronic products. The properties of magnetic fibres depend on the kind of magnetic material (the filler) included in the fibre matter, as well as on the filling degree. The degree of filling the fibre with grains of magnetic materials also influences its mechanical properties. Magnetic fibres may be used for the construction of textile magnetic coils. A magnetic coil, with or without a magnetic core, is the basic element of magnetic circuits which consist of parts of electric and electronic circuits. These circuits are in turn parts of various electromagnetic devices, such as inductive gauges and transmitters, as well as electromagnets which form the basis for electromagnetic actuators.

Key words: *magnetic fibres, multifunctional fibres, magnetic textile elements, magnetic coils, magnetic fillers, textronics.*

Introduction

Multifunctional fibres, also known as hybrid fibres, have recently begun to be manufactured world-wide. Independently of their natural textile features, they are characterised by new properties which increase the possibilities for their application in textronic products [9, 10]. These properties may be electroconductive, magnetic or piezoelectric, characterised by the transmission of radiation in general, and of light in particular. Multifunctional fibres, yarns, and nonwovens are currently elements of textile electro-engineering and electronics, and their additional properties are of greater importance than their mechanical properties.

A specific kind of multifunctional fibres – magnetic fibres, which are characterised by specific magnetic properties – are the subject of the presented elaboration. The particular aim of this paper is to describe the magnetic fibres we obtained on the basis of cellulose fibres, as well as current, already-tested applications, and those provided in the future.

A magnetic fibre may be symbolically presented as shown in Figure 1, where the magnetic properties are presented in analytical form by the equation $B = \mu H$ (assuming a linear arrangement), and in graphic form by the magnetisation dependency, with the magnetic stream Φ flowing along the fibre axis [7].

Figure 1. *Symbolic presentation of a magnetic fibre [11].*

Magnetic fibres create new possibilities for designing textile magnetic elements, and at the same electronic circuits and devices consisting of parts of intelligent clothing, for example those which can be used to monitor selected human physiological parameters .

Structure and manufacture of magnetic fibres

Magnetic fibres are manufactured by introducing ferromagnetic nano-particle powders into the fibre matter during fibre production. This results in an implementation of the ferromagnetic into the fibre, which becomes a macroscopic, monolithic material called a composite, as the polymer (the matrix) together with the powder filler make a discontinuous phase. These composites are also called electronic composites, as they have many applications in structures of microelectronic and nano-electronic micro-mechanical systems (MEMS) and bio-micro-mechanical systems (BioMEMS) [15].

The Lyocell process was the initial textile technology which we used to obtain fibres with magnetic properties. This method consists in obtaining fibres from concentrated cellulose solutions in N-oxide-N-methylmorpholine (NMMO) [1, 2]. In order to obtain an appropriate magnetic effect, powered modifiers with hard and soft magnetic properties are introduced into the spinning solutions. The modification performed at the stage of preparing the spinning solution is one of the most efficient methods of creating new fibre properties, as it enables the distribution of the modifier particles throughout the fibre's whole volume. Closing the modifier particles in the cellulose fibre matter guarantees the stability of the modification effect, in contrast to techniques based on surface processing.

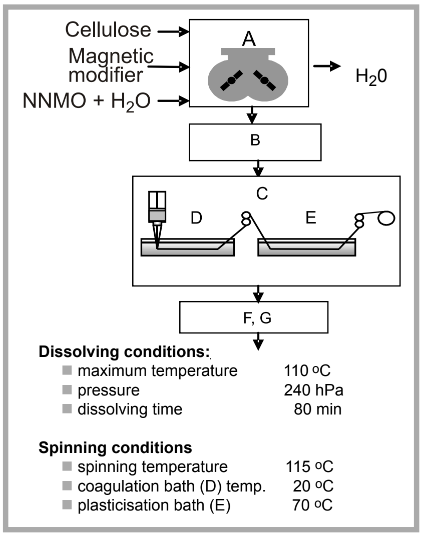

Figure 2. *Brief scheme of cellulose dissolving and spinning magnetic fibres together with the basic parameters of dissolving and of spinning conditions; A – dissolution unit, B – filtration, C – spinneret, D - coagulation (solidification) bath, E – drawing bath, F – take-up unit, G – dryer.*

By introducing appropriate modification substances into the fibre, it is possible to obtain differentiated effects, including the improvement of electrical conductivity [3], the decrease pf combustibility [4], shielding properties or conversion of UV radiation, as well as allowing for the manufacture of fibres characterised by sensory properties for a wide spectrum of parameters [5].

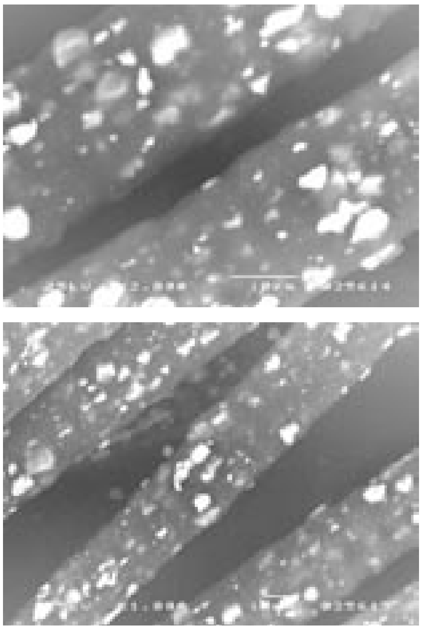

Figure 3. *Longitudinal view of the magnetic fibres we obtained.*

We span the fibres from NMMO solutions of cellulose by the dry-wet system shown schematically in Figure 2.

A mixture of hard and soft magnetic materials was used to modify the cellulose fibres. We selected barium ferrite $BaFe_{12}O_{19}$ (obtained from ferrous oxide Fe_2O_3 and barium carbonate $BaCO_3$) as the hard magnetic material and nano-crystalline alloy (obtained as a result of a controlled crystallisation of metallic glasses of the composition Fe-M-B(M=Nb, Cu, Hf, Zr, Si)) as the soft magnetic material. Both the modifiers used were introduced into the spinning solution in the form of powders with an average grain diameter of 8 μm.

The modification procedure presented above allowed us to obtain a high filling degree of the magnetic modifier in the fibre matter, of up to 50 wt% of the hard magnetic material, and up to 40 wt% for the soft magnetic material. These were the maximum experimentally-determined filler amounts which enabled fibres to be obtained using classical spinning methods. The fibres were immediately spun from the solution into the aqueous solidification bath. The fibres were spun at a velocity of 70 m/min, and a total drawing ratio of 70 was exerted.

The fibres manufactured were tested in order to estimate the magnetic effect obtained and the influence of the modifier's presence on the basic physico-mechanical fibre properties. The magnetic properties of the fibres were measured with the use of a LakeShore VSM 7307 magnetometer, (made in the USA) with an oscillating sample, whereas the strength properties were determined with the use of a Zwick Z2.5/TN18 tensile tester (made in Switzerland).

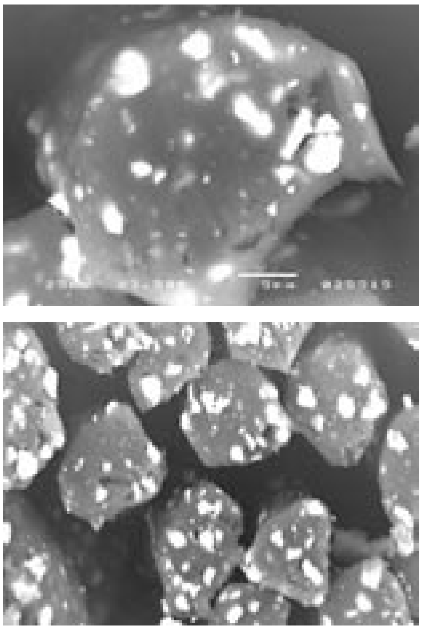

Figure 4. *Cross-sections of the magnetic fibres we obtained.*

The fibre fillers were magnetic granulates. The structure of the magnetic fibres obtained is presented in Figures 3 and 4, which show the fibres' longitudinal views and cross-sections. The white spots visible in all photographs are grains of the inserted magnetic material. The grains are randomly distributed.

A model may represent the elementary structure of magnetic fibres, where the path of the magnetic stream of the magnetic field Φ goes through the magnetic granules and the polymer. This is related to the magnetic reluctance R_{Fe} and the polymer reluctance R_P, and is shown in Figure 5.

Both reluctances can be calculated from the following equations:

$$R_P = l_p/(\mu_p S) \qquad R_{Fe} = l_{Fe}/(\mu_{Fe} S)$$

where:

R_P – the reluctance of the polymer,
l_P – the length of the path through the polymer between the ferromagnetic grains.
μ_P – the permeability of the polymer,
R_{Fe} – reluctance of the ferromagnetic.
l_{Fe} – length of the path through the ferromagnetic,
μ_{Fe} – the permeability of the ferromagnetic,
S – the elementary area of the ferromagnetic cross-section.

Textile magnetic cores

Textiles with magnetic properties may have various applications in textronic products. However, as the basic elements in magnetic circuits are permanent magnets, and magnetic cores which may implement magnetic air coils, the basic application of magnetic fibres and textiles is precisely as magnetic cores.

Magnetic fibres are used for constructing textile magnetic cores, which are subsequently applied as components of inductive transmitters and gauges, textile aerials, subassemblies of measuring and control circuits, as well as actuators. All of these devices may be used in clothing and intelligent textile products.

Magnetic properties of fibres

Introducing ferromagnetic powder into the diamagnetic cellulose fibres resulted in obtaining a composite of new magnetic properties. The hysteresis loops of the composite fibres obtained are shown in Figure 6. Experiments carried out indicated that the value of the residual magnetism induction of fibres, which included a hard magnetic, was only a part of the residual magnetism of the pure magnetic, and was related to the percentage volume content of the magnetic filler in the fibre. The value of the residual magnetism induction of barium ferrite was 0.177 T. The level of the fibres' field intensity of the coercive force was approximately equal to the value of the coercive force of the magnetic powder used, and equals 11.9 kA/m.

As the character of the magnetic parameters included in the fibres is maintained after spinning, we can assume that the ferromagnetic used is chemically resistant to the conditions of cellulose dissolving, as well as to the impact of the spinning solution medium. The chemical

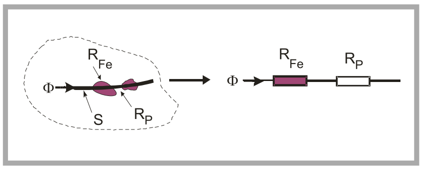

Figure 5. *Model of the magnetic fibre and its equivalent circuit [12].*

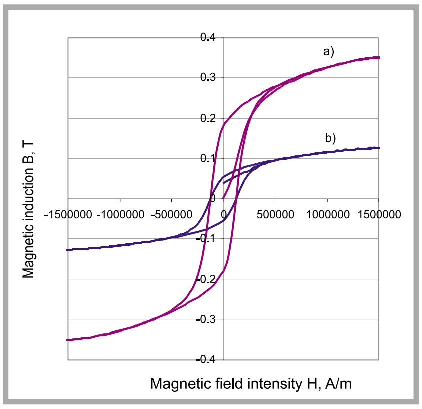

Figure 6. *Magnetic loops of magnetising a) barium ferrite (hard magnetic), and b) fibres including 50 wt% (23 vol%) of barium ferrite.*

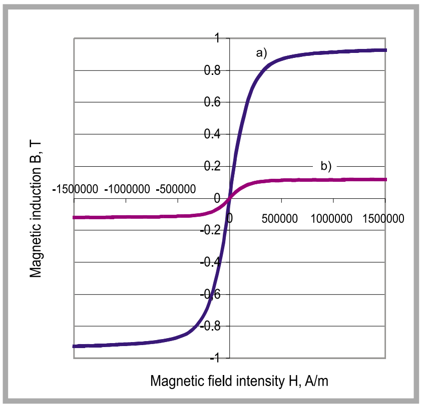

Figure 7. *Magnetic loops magnetising a) the nano-crystalline alloy (soft magnetic) and b) the fibres including 40 wt% (19 vol.%) of the nano-crystalline alloy.*

stability of the magnetic modifier is also indicated by the fact that its presence in the spinning solutions does not cause any changes in the polymerisation degree of the cellulose matrix of the spun fibres.

The nano-crystalline soft magnetic, whose hysteresis loops are shown in Figure 7, were characterised by a smaller chemical resistance than the magnetic hard ferrite. This behaviour may be testified by the lower (by 10.5%) value of the field intensity of the coercive force of the nano-crystalline magnetic included in the fibres, in comparison with the pure nano-crystalline magnetic, which is characterised by a value of 1.9 kA/m.

Improving the fibres' magnetic parameters, which means among other aspects increasing the value of the residual magnetism induction and of saturation induction, is possible only by introducing more magnetic active materials into the fibre. However, such possibilities are limited, as great amounts of the modifier in powder form worsen the spinning solution's processing ability. We assume that applying magnetic powder with smaller grain diameters (diameters below 3 μm) and a smaller range of size distribution could be a solution to this problem.

Physico-mechanical properties of the fibres

Fibre strength is a substantial parameter conditioning the practical possibility to apply magnetic fibres. As could be assumed, the presence of relatively large particles of the magnetic modifier in the fibre matter essentially influenced not only the fibres' tenacity (Figure 8), but also other strength parameters which we tested. This influence was caused by the increase in that content of the spinning solution which is not washed out during the fibres' solidification process. With the increase in the magnetic filler content, the yarn's linear density also increased, caused by the great difference in density between the fibre's components, and a decrease was also noted in the initial modulus and the elongation at break (Figure 9 and 10)

The diameters of fibres spun under the same conditions depended on the amount of the magnetic introduced, and were within the range from 15.1 μm to 18.8 μm. The effect of increasing the fibres' diameters by increasing the modifier amount included in the fibre may also be explained by the increase in that content of the spinning solution which is not washed out during the fibres' solidification process.

The worsening of the fibres' strength parameters, especially the tenacity of magnetic fibres, is also caused by significant differences between the properties of the composite's components. In such a case, during deformation of the fibre, discontinuities of its structure occur at the boundary between the cellulose matrix and the modifier particles, creating cracks which weaken the fibre's structure.

Textile magnetic coils

A magnetic coil, the basic element of electric and electronic circuits, is commonly constructed as a reel with windings wound onto it. A textile coil may be constructed from a woven fabric consisting the reel. The winding may be realised, as we demonstrated in [10], by the use of copper coil wire or conductive yarn. One of the essential advantages of textile coils is the possibility that the reel can change its form, starting from linear up to toroidal. The electro-conductive yarns, when used, should be characterised by high electrical conductivity, in order to obtain a low internal resistance of the coil windings. Inside the coil magnetic fibres are inserted, which fulfil the function of an

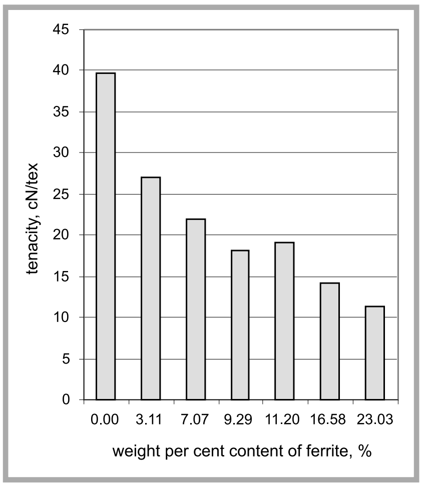

Figure 8. *Dependency of the fibres' tenacity on the ferrite content in the fibre.*

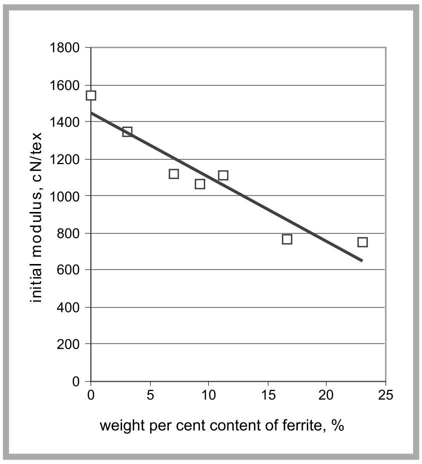

Figure 9. *Dependency of the fibres' initial modulus (at 0.3 % of elongation) on the ferrite content in the fibre.*

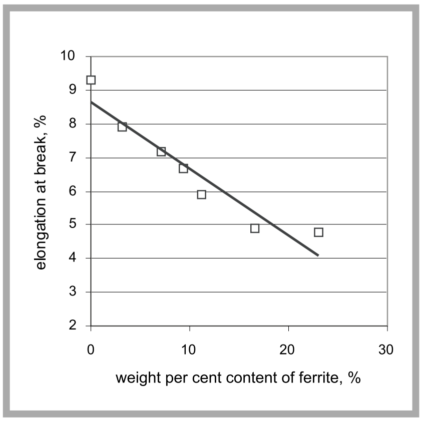

Figure 10. *Dependency of the fibres' elongation at break on the ferrite content in the fibre.*

elastic textile magnetic core. The design of a linear textile magnetic coil with magnetic fibres as the magnetic core, and metallic wires or electroconductive yarn as the winding, is presented in Figures 11 and 12 [10].

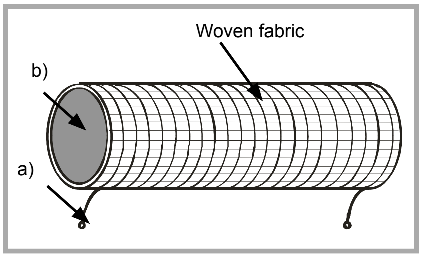

Figure 11. View of a textile magnetic coil with textile magnetic core [10]; a) wire or conductive yarn, b) magnetic fibres.

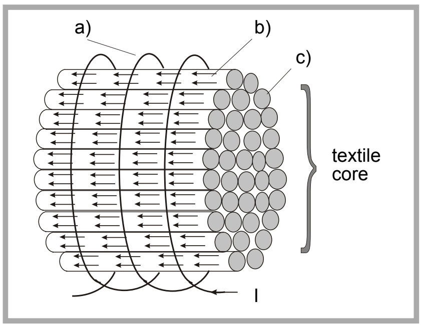

Figure 12. Schematic view of the design of a textile magnetic coil with textile magnetic core; a) wire or conductive yarn, b) magnetic field lines, c) magnetic fibres.

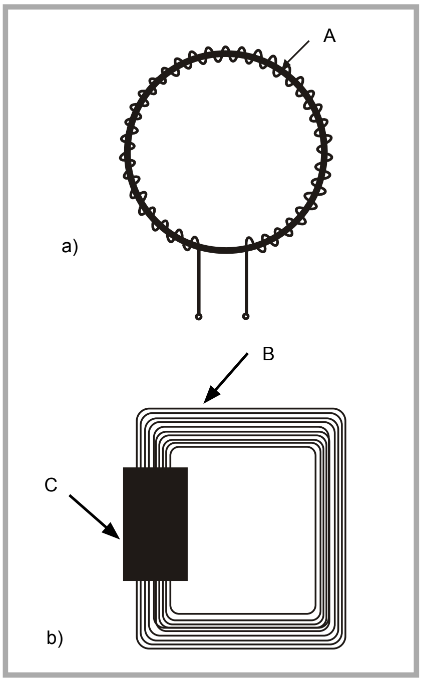

Figure 13. Textile magnetic coils; a) toroidal coil with a core of a singular magnetic fibre, b) coil with multi-fibre magnetic core; A) magnetic fibre with diameter of 0.0018 cm, B) magnetic core, C) winding.

Magnetic cores constructed of magnetic fibres do not have a monolithic character (Figure 12), Independently, as a variant, the magnetic core may also be constructed of a magnetic nonwoven with ferromagnetic granulate included.

An elementary magnetic toroidal coil with a core of a singular magnetic fibre and a coil with a multi-fibre magnetic core are presented in Figure 13.

As mentioned earlier, the magnetic properties of magnetic fibres depend on the properties of the ferromagnetic used. The properties of magnetic fibres may be determined on the basis of the following properties: the relative magnetic permeability μ_r, the non-linear ambiguous magnetising curve with a hysteresis loop $B = f(H)$, the possibility of permeable magnetising, and the occurrence of anisotropy and magnetostriction [8, 13, 14].

Macroscopic model of a textile magnetic coil

The elasticity of a magnetic fibre or a textile magnetic core influences both the mechanical as well as the magnetic properties of the fibre. A macroscopic two-parameter structural model of a magnetic fibre or magnetic textile core, which considers mechanical and magnetic phenomena, is presented in Figure 14. The deformation of the magnetic fibre causes deformation of the crystalline net of the ferro-magnetic, and at the same influences the changes in magnetic permeability $\Delta\mu$. The tensions and deformations of the fibre cause a change in the geometric fibre parameters. The changes in the fibre permeability and in the geometrical dimensions together cause a change in the fibres' reluctance ΔR_m.

Conclusions

Magnetic fibres are fibres determined by their mechanical and magnetic properties, and are characterised by the following features:

- The magnetic properties depend on the kind of the implemented magnetic filler and its percentage content by volume in the fibre matter.
- The filling degree of the fibre by the magnetic is limited by the fibre's strength. The boundary values which we stated were 40 wt% for the soft magnetic material, and 50 wt% for the hard material.

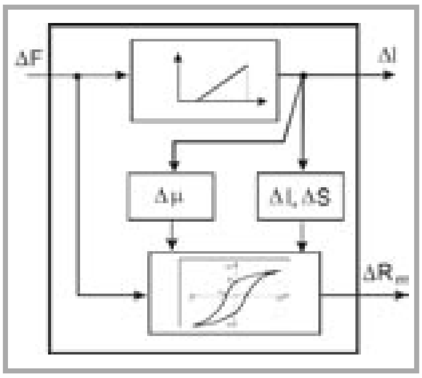

Figure 14. Model of a magnetic fibre; ΔF – change of force acting on the fibre; Δl – change of the fibre's length, ΔS – change of the cross-section area, $\Delta\mu$ -change of the magnetic permeability, ΔR_m - change of the fibre's reluctance [11].

- Exceeding the boundary values of the filling degree caused an essential decrease in the fibre's strength under the conditions used by us (grain diameters of the magnetic fillers of about 8 μm, and fibre diameters within the range from 15.1 mm to 18.8 mm).
- Based on theoretical considerations, it can be stated that improving the properties of magnetic fibres is possible by using magnetic materials with high energetic density and smaller grain diameter, which would enable us to increase the filling degree.
- It was proved that magnetic fibres can be elements of magnetic cores, which as parts of textile transmitters, gauges, and actuators may be broadly applied in textronic, intelligent clothing products.

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References

1. *Łaszkiewicz, B., 'Obtaining cellulose fibres without the use of carbon disulfide', A.C.G.M. LODART S.A., Łódź 1997.*
2. *Woodings, C. R.: 'The development of advanced cellulosic fibres', Int J Biol Macromol, 1995, Vol. 17, Issue 6, p. 305-309.*
3. *Rubacha, M,., Urbaniak-Domagała, W,., Łaszkiewicz, B., 'Electroactive cellulose fibres', 4th International Conference ELTEX 2000, Lodz, Poland, p. 200.*

4. Seddon, H,., Hall M., Horrocks, A. R., 'The flame retardancy of Lyocell fibres', Polym Degrad Stabil, 1996, Vol. 54, Issue 2-3, p. 401-402.
5. Łaszkiewicz, B., Rubacha, M., Czarnecki, P., Niekraszewicz, B.: 'Cellulose Fibres As Chemical Sensors', Conference Proceedings', 9th International Meeting on Chemical Sensors, Boston, USA, July 7-10, 2002, p. 393.
6. Łaszkiewicz B., Czarnecki P., Kulpiński P., Niekraszewicz B., Rubacha M., 'Present status and future potential of smart fibers and fabric', 8th Int. Scien. Confer. November 2004, Łódź, Proceedings,
7. M. Leonowicz M., Rubacha M., Kulpiński P., Łaszkiewicz B., Liu Z., Davies H. A., 'Processing and Properties of Soft Magnetic Cellulose Fibres'. 3rd Int. Confer. on Advanced Manufacturing Technology. Kuala Lumpur, May 2004.
8. Rawa H., 'Elektryczność i magnetyzm w technice', Wydawnictwo Naukowe PWN, 2nd edition, Warszawa 2001.
9. Gniotek K., Stempień Z. Zięba J., 'Textronics – a new branch of knowledge' (in Polish), Przegląd Włókienniczy, No. 2, 2003.
10. Zięba J., Polish Patent Application ('Method of obtaining a magnetic coil destined especially for placing into textile products' (in Polish).
11. Zięba J., 'Magnetic fibres' (in Polish), Proceedings of the 6th Seminar for Textronics, 'Measurement and Automation in Textile Engineering'. Konopnica, 2005.
12. Zięba J., 'Modelling of magnetic fibres' (in Polish), Proceedings of the 7th Seminar for Textronics, 'Measurement and Automation in Textile Engineering', Konopnica, 2006.
13. Ciureanu P., Rudkowska G., Rudkowski P., Ström-Olsen J.O., 'Magnetoresistive sensors with rapidly solidified permalloy fibers', IEEE Transaction on Magnetic, vol.29, nr 5. September 1993.
14. Rudkowski P., Ström-Olsen J.O., 'Frequency, magnetic field and size dependence of properties of amorphous soft-magnetic fibers', IEEE Journal of Magnetism and Magnetic Materials 249, 2002, 85-88.
15. Taya M., 'Electronic composites, modeling characterization processing, and MEMS application', Cambridge University Press, Cambridge 2005.

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