Perspectives of application of nanostructured composites for new diagnostic systems for transcranial magnetic stimulation

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Abstract. The paper presents a study of the prospects for using nanostructured composites for new promising diagnostic systems of transcranial magnetic stimulation. A principle of operation of a new device of transcranial magnetic stimulation using nanostructured composites is proposed. The system wires Cu-Nb are considered as an example of nanostructured composites. The analysis was carried out from the point of view of electrophysical, thermophysical and strength properties. According to the study, conclusions were made about the prospects for using materials of this class as a functional material for a stimulating probe of a portable device of transcranial magnetic stimulation.

Keywords: Transcranial magnetic stimulation, nanostructured composites, diagnostic systems.

Introduction

Nowadays, there is undeniable data on the effects of a magnetic field on the cerebral cortex, helping to reduce pain from headaches and radiculitis types of pain. There are data on the effects on brain areas responsible for appetite and perception of new information, which is the basis for creating devices that stimulate learning languages or reduce cravings for excessive food consumption. The most common method of non-surgical exposure to areas of the brain is transcranial magnetic stimulation (TMS). This method consists in the fact that the magnetic field, acting on the motor area of the cerebral cortex, causes a reduction in the corresponding peripheral muscles. Under the influence of alternating magnetic fields on the brain tissue, induction of weak electric currents that stimulate nerve cells occurs. [1-2]. The advantages of this method are the high penetrating ability (even through bone, cartilage and muscle tissue), painlessness (created by the electromagnetic field is not able to excite pain receptors) and ease of the procedure. Transcranial magnetic stimulation practically does not cause side effects, sometimes there may be a feeling of discomfort or a slight headache. [1-2].

Transcranial magnetic stimulation is currently used in psychiatry, neurology, pediatrics, traumatology and other areas of medicine for non-invasive diagnosis and treatment of many diseases [3-6]. Now the TMS technique is used only in the conditions of stationary clinics with the use of expensive hardware systems and sophisticated software. The disadvantages of such installations are the mandatory need of medical personnel for the procedure, the weight and size of the device.

The current problem is the creation of a portable device, which may be used even on an outpatient basis. There are several foreign companies that are developing such type of devices, while there are no such products on the Russian market. The development of a domestic device is determined by the importance of solving the national problem of import substitution of special products with products of Russian origin.
The principle of operation of the device of transcranial magnetic stimulation using nanostructured composites

Transcranial magnetic stimulation, originally proposed as a diagnostic and research method, quickly went beyond functional research. The emergence of the ability to non-invasively stimulate brain structures, and with the help of inhibitory and activating mechanisms to influence the higher cortical functions and mental status of the patient, opened up new horizons and areas of TMS application. High-tech magnetic stimulators, as well as multifunctional programming of magnetic pulse parameters, provided the necessary safety criteria and made transcranial magnetic stimulation one of the reliable therapeutic methods.

The principle of rhythmic transcranial magnetic stimulation is to use a series of pulses sent at different frequencies (number of pulses per second). Induced magnetic field can cause an inhibitory or stimulating effect, stimulation with a low frequency (less than 1 Hz), has an inhibitory effect on cortical processes, and stimulation of more than 1 Hz increases the excitability of cortical motor neurons, which is used in the treatment of a wide range of mental diseases: Depression, auditory hallucinations in schizophrenia, treatment of obsessive-compulsive disorder, treatment of schizophrenia (negative symptoms), panic disorders, post-traumatic stress disorders.

The design of a stationary device is made in the form of a power supply and control unit, combined, as a rule, in a single case, as well as an external stimulating probe, which is a cooled inductor, producing an alternating magnetic field of a given intensity and frequency with a predetermined frequency.

The inductor is a ring coil with a magnetic core of a special configuration. Inductors can vary in the number of turns, the material of the core and the conductor, and also use two or more inductors in different configurations.

For reducing the size of the power supply and the size of the inductor it is necessary to apply new materials and technologies that allow more efficiently accumulate, use and convert electrical energy. The most critical to changing the geometric dimensions of the installation units are a step-up transformer, electrical energy storage devices, an inductor and the entire high-voltage part of the system. The dimensions of the step-up transformer and energy storage devices are directly dependent on the used high-voltage voltage and the generated power. These parameters, in turn, are due to the design of the inductor, since for generating a powerful magnetic field with an induction of about 1 T, it is necessary to create a current pulse of sufficient magnitude in a short period of time, which can be induced only at high voltages of about 1 kV. At the same time, a current with a force of thousands of A passes through the inductor conductor, which causes strong heating of the conductor and the dissipation of electrical energy into heat. As a result, for creating a magnetic field of the required size, it is necessary to use a sufficiently powerful current pulse.

Obviously, in order to reduce the dimensions of these system nodes, it is necessary to optimize the parameters of the inductor, reducing energy dissipation and heat losses, which, at lower pulse powers, allow creating a magnetic field of similar magnitude. This can be achieved by replacing the used materials of the conductor and inductor core, as well as by changing its design.

Artificial permanent and alternating magnetic fields can be created with the help of permanent magnets, inductors, and electromagnets. In the terminology established in the scientific literature on magnetobiology and magnetic therapy, the source of the artificial magnetic field is called the inductor.

Inductors in the form of solenoids, cylindrical and non-cylindrical short coils, electromagnets with cores of various configurations made of various materials are widely used for creating variable, pulsating and pulsed magnetic fields in magnetic therapy. Any source of a magnetic field has different poles; it has closed lines of force (the direction is from north to south). At sources of an alternating magnetic field, the poles change periodically in accordance with the change of the current direction.

Due to an inductor with a short cylindrical coil creates a magnetic field with the highest inductance, has the greatest impact area and can be used in a wide range of medical procedures compared to other types of inductors [7], it was decided to focus on this type of inductor for further consideration.
Figure 1 shows the developed schematic diagram of the creation of a magnetic field of a given induction in the case of the designed technical system—a stimulating probe of a portable transcranial magnetic stimulation device.

![Schematic diagram of the creation of the magnetic field of a given induction in the transcranial magnetic stimulation device](image)

**Figure 1** Schematic diagram of the creation of the magnetic field of a given induction in the transcranial magnetic stimulation device

**Analysis of the prospects for the use of nanostructured composites as a functional inductor material device for transcranial magnetic stimulation**

Replacing the conductor material should also significantly affect the parameters of the inductor. In existing inductors, copper is usually used as the most optimal material in terms of cost and conductivity characteristics. There are standard materials that have lower electrical resistance than copper, for example, silver and gold, but, firstly, they are rather expensive, and secondly, they have unsatisfactory mechanical characteristics. In this regard, the use of superconductors as an inductor conductor is of the greatest interest. However, there may be significant technological problems associated with the operating temperature of such materials. As a rule, the phenomenon of superconductivity is observed in materials at temperatures of liquid helium or nitrogen. There is also a whole class of high-temperature superconductors, but for the most part, they are complex polymers and at this stage of development, technology is not technological at all. It is possible to use superconductors at the temperature of liquid nitrogen when the problem of cooling inductors is solved in parallel that would have occurred with the use of any other standard conductors.

For selecting a functional inductor material - conductive material - various options were considered, including widely used materials - brass, copper, steel. Comparative analysis was carried out for their electrophysical and other service properties. Along with the known materials, a special class of superconductors was of interest – such nanostructured composite materials as compounds Cu-Nb or their analogs. The task was set to study the electrophysical properties of wire samples from such nanostructured composites as Cu-Nb to solve the main problem—to determine the possibility and prospects of the use of materials of this type as an inductor of the transcranial magnetic stimulation device.

A significant number of studies of two-component materials developing technically suitable high-strength conductors with a nanocrystalline microstructure scale were carried out on the system Cu-Nb. The obtained «in situ» composites were subjected to intensive deformation for obtaining a nanocrystalline structure.
Such composites are called «in situ» composites [8], since during deformation of a molded compact billet; both phases are relatively equally plastically deformed with the formation of ribbon long fibers distributed in a matrix material.

To obtain «in situ» composites there are criteria to be met of the system by components:
- no wide area of solid solutions in the solid state;
- complete solubility in the liquid state;
- the absence of intermediate intermetallic compounds in the state diagram;
- good deformability;
- low mutual solubility at low temperatures.

There are 2 more criteria in the development of conductors with the highest electrical conductivity:
- the high electrical conductivity of one of the components;
- the high volume fraction of one of the components in a composite.

The analysis was carried out on the basis of theoretical and experimental data presented in the works [9-11].

Based on the experimental data on studies of thin wire samples in order to achieve the maximum strength properties, which are achieved by plastic deformation, it follows that in microcomposites composed of components with a combination of lattices FCC-BCC (Cu-Nb, Cu-Ta, Cu-Fe) absolute values of tensile strength have higher values than for composites with a combination of gratings FCC-FCC (Ag-Cu, Ag-Ni). The nature of this effect is complex, but it is sufficient to note here that one of the main factors is that in the first case BCC fibers acquire a pronounced ribbon cross-section. In the case of FCC, the fibers maintain a cylindrical shape.

It is known that composites with core fibers with a cross section in the form of ovals, elongated along one axis, have 2 times higher stiffness than composites with an equal proportion of circular fibers.

When considering the correlation of microstructure-strength, it was noted that the strength of composites Cu-Nb with a percentage of niobium 12% and 20% equally correlated with the distance between the fibers for both alloys. Based on this, it can be assumed that the distance between the fibers (the average distance of dislocations in the copper matrix) determines the strength of these composites [12-14]. If this statement is true, the niobium fibers play the role of barriers preventing dislocations from sliding in the copper matrix. In composites Cu-Nb the cycle of deformation hardening-return-recrystallization leads to microstructural grinding of the grain structure in the copper matrix, which begins to be determined by the distances between the fibers Nb for large degrees of deformation. The assumption that the critical degree of deformation for dynamic recrystallization of niobium is higher than for copper confirmed that there are practically no recrystallized niobium grains.

To be used as strengthening materials for the inductor of the TMS device, the developed material has to be sufficiently thermally stable and exhibit mechanical strength after prolonged heat treatment at high temperatures. As a thermally unstable, the use of conductors of such systems as Cu-Ag is not desirable as reinforcing elements. Cu-Fe shows ferromagnetic properties of technical elements, but the use is not possible. Thus the system Cu-Nb was chosen.

Consider the dependence of thermal conductivity on the temperature of the two materials. Figure 2 shows that thermal conductivity decreases with an increase in temperature.
For safe operation of the transcranial magnetic stimulation device, it is necessary to carry out work to increase the emitted heat flow for more efficient heat removal. Cu has heat conductivity with an increasing temperature higher than that of composite material Cu-Nb.

With increasing temperature coefficient of linear thermal expansion (CLTE) increases (Fig. 3). At $T=200\,^\circ\text{C}$ CLTE $\alpha^*=17,42\cdot10^6\,\text{C}^{-1}$ for Cu, and for Cu-Nb $\alpha^*=16,12\cdot10^6\,\text{C}^{-1}$.
It should be added that the content of niobium in Cu increases the corrosion resistance of the material [10], which increases the service life of the device. Heat losses that occur when heat is transferred from the coil to the heat carrier go for heating the structure. Therefore, if the magnitude of such losses is high, then under the action of temperature, some elements may begin to deteriorate.

According to the study, conclusions were made about the prospects for using materials of this class as a functional material for a stimulating probe of a portable device for transcranial magnetic stimulation. The use of Cu-Nb nanostructured composites as a material for the wires of the inductor coil of a TMS device would improve the safety and service life of medical devices using the transcranial magnetic stimulation method.

Summary
The prospects for using nanostructured composites in the device for transcranial magnetic stimulation have been studied. The principle of operation of a new device for transcranial magnetic stimulation using nanostructured composites is presented. According to the results of a comparative analysis of various types of inductors used in medical practice and the characteristics of the fields created by them (solenoid, flat cylindrical coil, Helmholtz coil), it was decided to focus on the second option. To select a functional inductor material - conductive material - various options were considered, including widely used materials - brass, copper, steel. Comparative analysis was carried out for their electrophysical and other service properties. Along with the known materials, a special class of superconductors is of interest – such nanostructured composite materials as Cu-Nb compounds or their analogs. According to the results of the study, conclusions are made about the prospects of using materials of this class as a functional material of a stimulating probe of a portable transcranial magnetic stimulation device.

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References
[1] Simone Rossi, Mark Hallett, Paolo M. Rossini, Alvaro Pascual-Leone and The Safety of TMS Consensus Group. Safety, ethical considerations, and application guidelines for the use of transcranial magnetic stimulation in clinical practice and research, Clinical Neurophysiology. 120 (2009). 2008-2039.
[2] Mark S. George, Sarah H. Lisanby, Harold A. Sackeim. Transcranial magnetic stimulation. Applications in Neuropsychiatry. Arch Gen Psychiatry. 56 (1999). 300-311.
[3] Erofeev A. I. et al. Use of optogenetic technology in cell culture models //Journal of Physics: Conference Series. – IOP Publishing, 2016. – T. 741. – №. 1. – C. 012067.
[4] Erofeev A. I. et al. Use of optogenetic technology in cell culture models, implantable device to works in slices and live animals //Opera Medica et Physiologica. – 2016. – №. S1.
[5] Matveev M. V. et al. Implantable devices for optogenetic studies and stimulation of excitabile tissue //St. Petersburg Polytechnical University Journal: Physics and Mathematics. – 2015. – T. 1. – №. 3. – C. 264-271.
[6] Matveev M. V. et al. Implantable optical-electrode device for stimulation of spinal motoneurons //Journal of Physics: Conference Series. – IOP Publishing, 2016. – V. 741. – Is. 1. – P. 012071.
[7] Kisten O.V., Davydov M.V., Evstigneev V.V., Regularity of the distribution of induced currents during transcranial magnetic stimulation and its use in patients with epilepsy. ArsMedica. 12 (2010). 79-85.
[8] Bobkova T. I., Farmakovskii B. V., Bogdanov S. P. Creation of composite nanostructured surface-reinforced powder materials based on Ti/WC and Ti/TiCN used for coatings with enhanced hardness //Inorganic Materials: Applied Research. – 2016. – T. 7. – №. 6. – C. 855-862.

[9] W.A.Spitzig, A.R.Pelton, F.C.Laabs, Characterization of the strength and microstructure of heavily cold worked Cu-Nb composites. Acta Metallurgica. Vol, 35, 10 (1987). 2427-2442.

[10] D.A.Hardwick, C.G.Rhodes, L.G.Fritzemeier, The effect of annealing on the microstructure and mechanical properties of Cu-X microcomposites. Metallurgical Transactions A, 24A (1993). 27-34.

[11] A.V. Putilov, A.K. Shikov, V.I. Pantsyrny, A.E. Vorobyova, V.A. Drobyshev, Creation of superstrong nanostructured microcompositional electrotechnical Cu – Nb wires by plastic deformation, Non-ferrous metals. 3 (2008) 77-83.

[12] Kononov A. A., Zotov O. G., Shamshurin A. I. Distribution of Crystallographic Orientations in an Anisotropic Electrical Steel Under Rolling Stages //Metal Science and Heat Treatment. – 2014. – T. 56. – №. 7-8. – C. 449-453.

[13] Kolbasnikov N. G. et al. Investigation of structure, rheological and relaxation properties, and stress relaxation kinetics in nanocrystalline beryllium at hot rolling temperatures //Nanotechnologies in Russia. – 2014. – T. 9. – №. 1-2. – C. 65-72.

[14] Matveev M. A., Kolbasnikov N. G. High-temperature plasticity of microalloyed steel //Steel in Translation. – 2016. – T. 46. – №. 4. – C. 285-289.