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Modification of the titanium surface of biomedical electronics to improve electrophysical properties

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Modification of the titanium surface for biomedical electronics in order to improve electrophysical properties was performed by forming conductive coatings based on single-walled carbon nanotubes (CNTs). This study investigates how the preparation parameters of carbon-dispersed media affect the properties of the coatings they form. The CNTs were stabilized using various surfactants and subjected to ultrasonic homogenization and centrifugation with varying key parameters. The homogeneity of the dispersed media was assessed by optical spectroscopy and dynamic light scattering. The electrophysical properties of the manufactured coatings were investigated by measuring the surface resistance. It has been found that optimization of processing parameters, such as power and homogenization time, contributes to the destruction of agglomerates, increases the stability of dispersions and improves the electrical conductivity of the formed coatings.

Keywords: single-walled carbon nanotubes, surfactants, specific electrical conductivity, conductive coatings, titanium surface.

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Introduction

Titanium and its alloys are widely used in biomedical electronics for the fabrication of implantable electrodes, sensors, neurostimulators and cardiac pacemakers owing to their excellent corrosion resistance, biocompatibility and mechanical strength. However, the relatively low electrical conductivity of pure titanium limits its use in devices where efficient transmission of signal between biological tissues and electronic part of the system is required [1,2].

One of the promising approaches to improve electrophysical properties of titanium surfaces is their modification with carbon nanotubes (CNT) [3,4]. Due to their high conductivity, large specific surface area and chemical resistance, CNT can significantly increase the efficiency of electrical signal transmission and provide fine-tuned coating properties for specific functional tasks. However, weak adhesion of CNT to a metal substrate is a problem because it reduces the durability and stability of coatings.

One of the most effective methods of increasing the adhesion strength of CNT to a titanium substrate is laser treatment, accompanied by local heating and short-term melting of the surface layer of metal [5,6]. When exposed to high-intensity pulses, carbon atoms diffuse from the CNT layer into the near-surface zone of titanium, which leads to the formation of carbide phases, primarily TiC [7]. The resulting transition layer provides mechanical fixation of the nanotubes and improves electrical contact between the carbon network and the metal substrate. In addition, laser treatment helps to smooth the surface relief, reduce contact resistance and create a stable three-dimensional conductive structure [6]. This combination of effects makes it possible to obtain composite coatings „Ti–CNT/TiC“ with increased electrical conductivity, wear resistance and stability under operating conditions of implantable electronic systems. However, the effectiveness of laser-induced TiC formation greatly depends on the uniformity and quality of the initial carbon layer, which requires preliminary preparation of a stable, homogeneous dispersed medium based on CNT and its controlled application to titanium surface.

CNT tubes are prone to aggregation due to strong inter-tubular van der Waals interactions and high specific surface area, which hinders their uniform distribution in aqueous solutions. To stabilize the dispersions and prevent agglomerations the surface-active substances (SAS), in particular, sodium cholate (SC) and sodium deoxycholate (DOC) [10]. SC and DOC are biliary salts. Bile acids are steroidal acids synthesized in the liver from cholesterol, which act as fat emulsifiers and have amphiphilic properties due to the presence of hydrophobic steroid backbone and hydrophilic groups in the molecule. Biliary salts, including SC and DOC, are sodium salts of these acids and, due to their amphiphilic nature, interact effectively with CNT, contributing to their stabilization and dispersion in aqueous media. The hydrophobic part of these surfactants interacts with carbon surface of the nanotube, while the hydrophilic part is oriented outward, forming a stabilizing layer and preventing the nanotubes from sticking together (Fig.1)

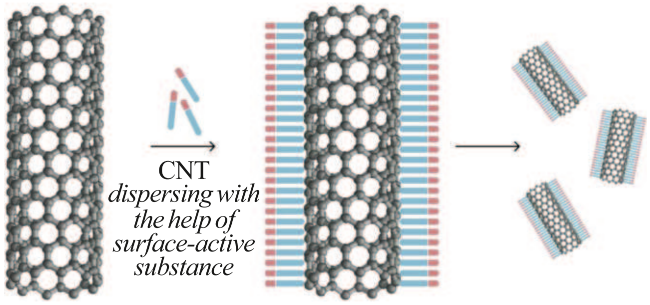

Figure 1. CNT and surfactant interaction diagram.

SC and DOC are selected because of their effectiveness in stabilizing single-walled carbon nanotubes (SWCNT) in aquatic systems and their good biocompatibility, which is important for applications in biomedical electronics. Yet, there are key differences between them: DOC is more hydrophobic because it contains fewer hydroxyl groups in the steroid carcass, which enhances interaction with the carbon surface and increases the dispersion efficiency of nanotubes. SC, being more hydrophilic, forms stable aqueous micelles, but has poorer adhesion to the nanotube [10].

The quality of the resulting dispersed medium, and, consequently, the uniformity of the applied coating, is determined by the parameters of its preparation. The time and power of ultrasonic homogenization [9] have a significant effect on the degree of dispersion.

Ultrasonic homogenization is accompanied by the development of cavitation processes underlying the mechanism of disaggregation of carbon nanostructures [11]. The short-term formation and implosion of cavitation bubbles create locally high pressures and micro-jet flows, causing significant shear stresses in the volume of the liquid [12]. These mechanical effects effectively damage the large CNT aggregates and contribute to their individualization, as well as provide a more complete coating of nanotubes with surfactant molecules [13,14]. As a result, stable „CNT-surfactant“, complexes are formed preventing the following aggregation.

Centrifugation is used as a method for assessing the stability of dispersed systems after ultrasonic treatment [15]. When impacted by a centrifugal field, aggregated and insufficiently stabilized particles precipitate faster, while stable dispersed fractions, completely covered with surfactant molecules and not prone to agglomeration, remain in suspension. Thus, the degree of transparency of the settling phase, the uniformity of particle distribution, and the absence of significant precipitation after centrifugation serve as indicators of stability of the formed dispersed medium [16]. Due to the combination of an ultrasonic treatment and a subsequent stability control by centrifugation the effectiveness of the surfactants used in preventing nanotube aggregation may be estimated in perspective.

Thus, this paper presents an approach to modifying a titanium surface for biomedical electronics. In order to improve the electrophysical properties, the influence of key parameters of the dispersed media preparation (time and power of ultrasonic homogenization, centrifugation modes) on the characteristics of SWCNT- and SC/DOC surfactant based coatings was investigated. Optical spectroscopy and dynamic light scattering were used to evaluate the uniformity and stability of suspensions, which directly correlates with the quality of the obtained coatings. The key criterion for the effectiveness of surface modification was the measurement of the electrical conductivity of coatings obtained on titanium substrates. As a result, optimal conditions for the synthesis of dispersed media have been determined, ensuring the formation of homogeneous and highly conductive coatings, which becomes the basis for subsequent laser modification in order to obtain composite structures „Ti–CNT/TiC“ with specified electrophysical properties.

1. Materials and methods of research

Section 1 outlines the materials and methods of research. The list of materials used is given, indicating their main technical characteristics. The developed method of titanium substrates surface modification is described in detail, which consists in the formation of a conductive coating by sputtering the stabilized SWCNT-based dispersions. To control the quality and uniformity of the prepared dispersed media, methods of optical spectroscopy in UV and visible regions and dynamic light scattering were used to assess the degree of nanotubes aggregation and the stability of suspensions. The key stage of the study included evaluation of the surface modification effectiveness, for which the technique of measuring the surface electrical resistance of the formed coatings using the four-probe method was used.

1.1. Materials used

To prepare the dispersion media the SWCNT Tuball 01RW03 (OCSiAl, Russia) was used. The nanotubes synthesized by chemical vapor-phase deposition (CVD) were characterized with a diameter (1.6 ± 0.4) nm, and length of $5\,\mu$m with a purity of not less than 99.9 %. Two kinds of surfactants were used as dispersing agents: SC and DOC (neoFroxx, Germany). The mass ratio of the components in the resulting dispersed medium was 0.1 mg/ml of SWCNT: 0.9 mg/ml of surfactant, which ensured the stability of the suspension and prevented agglomeration of nanotubes. All experiments were conducted using distilled water with a specific conductivity $5.1 \cdot 10^{-4}$ S/m and pH from 6.8 to 7.0 at $T = 298.15$ K.

1.2. Ultrasonic homogenization

The obtained dispersed mixtures were subjected to ultrasonic disaggregation using a Q700 homogenizer (Qsonica, USA). The mixtures were treated at a temperature of

(20 ± 2) °C and amplitude of ultrasonic vibrations of 25% of the device's nominal power.

To study the kinetics of dispersion, suspension samples were taken at equal 20-min intervals during 80 min ultrasonic treatment. The selected samples were used for the subsequent analysis of optical characteristics and nanotubes dispersing degree.

1.3. Centrifugation

The effect of centrifugation on the kinetic stability of dispersed media was studied in two consecutive stages using a laboratory centrifuge CM-6M (Elmi, Latvia).

At the first stage, with a fixed treatment time of 30 min, the rotor speed varied in the range from 100 to 3500 rpm with a step of 1000 rpm. In the second stage, on the contrary, the rotor rotation speed was constant and was 3500 rpm, while the centrifugation time varied — 60, 90 and 120 min. After each cycle of centrifugation, the optical density of the filler liquid was analyzed.

The stability of a dispersed system is estimated based on the fact that the quantitative content of particles remaining in suspension in the filler liquid directly correlates with its kinetic stability. In conditions of high dispersion stability, the optical density of the supernatant shall remain unchanged over time, which indicates the absence of any significant aggregation and sedimentation of particles. On the contrary, a decreased optical density evidences a progressive aggregation and precipitation of particles, and hence, loss of the dispersion stability.

1.4. Application of coatings on titanium substrates

SWCNT carbon coatings were formed by sputtering onto a pre-prepared titanium surface of glass substrates, acting as a medical device.

The titanium surface on cleaned, degreased glass substrates was formed using magnetron sputtering in an argon atmosphere at an operating pressure of $3 \cdot 10^{-3}$ Torr, constant power of 1000 W and process duration of 24 min. As a result, solid titanium layers with a thickness of (200 ± 10) nm were obtained which had high uniformity and good adhesion to the substrate.

The carbon coating was formed using an automated sputtering apparatus with controlled solvent evaporation. The samples described in sections 1.1 and 1.2 were used as dispersed media for sputtering. The deposition process was carried out on an automated apparatus equipped with a precision sputtering system and a thermostatically controlled substrate holder. The specifics of this method included a synchronized effect of two factors: the deposition of a dispersed medium and the instantaneous evaporation of the solvent, leading to the „fixation“ of CNT on the substrate surface. The dispersion medium under pressure of 2 bar was supplied through a 0.5 mm nozzle onto the substrate preheated up to (100 ± 5) °C. The „nozzle-substrate“ distance was 10 cm, which ensured optimal formation of the aerosol flare. The sputtering head was moving with a speed of 1 cm/s, which contributed to the uniform distribution of the material. After every ten passes, a technological pause of 5 seconds was made to completely remove the solvent. The thickness and uniformity of the deposited layers were monitored and evaluated by optical profilometry using S Neox profilometer (SENSOFAR, Spain). The thickness of each sputtered layer was ~ 30 nm. The total number of applied layers was 200, which ensured a dense and uniform coating with a thickness of $\sim 6\,\mu$m with reproducible parameters.

1.5. Measurement of optical and electrophysical properties

Optical characteristics of SWCNT-based dispersed systems with sodium cholate (SWCNT_SC) and sodium deoxycholate (SWCNT_DOC) was defined by method of spectrophotometry within $200 - 1100$ nm bands with a 2 nm step and scanning rate of 300 nm/min. Distilled water was used as a support solution. The measurements were carried out with automatic correction of background scattering and temperature stabilization of the samples.

The dynamic light scattering (DLS) method was additionally used to determine the hydrodynamic radius of the particles and assess the degree of dispersion. Experimental measurements were performed on a specialized Photocor Complex (Photocor, Russia). Samples of dispersed media were placed in disposable polystyrene cuvettes (Brand, Germany). The measurement protocol provided for 10 consecutive scans for each sample with three independent repeats. The detection angle was 90°.

The electrophysical characteristics of the obtained coatings were determined by four-probe measurements using a precision digital multimeter 34401A (manufacturer Keysight Technologies Inc., USA). The electrical conductivity of the samples was calculated from the measured resistance values:

$$\sigma = \frac{1}{r},$$

where σ — conductivity of samples, r — resistivity of samples.

2. Results and discussion

Section 2 shows the measured optical characteristics of the formed dispersed samples, as well as their dependence on the parameters of ultrasonic homogenization and centrifugation. The conductivity of samples obtained under various conditions of the dispersed media preparation were comparatively analyzed, and optimal conditions for obtaining coatings with minimal resistivity and a high degree of uniformity were found.

Additionally, the effect of the structural specifics of new Ti-SWCNT composites on their potential use in biomedical

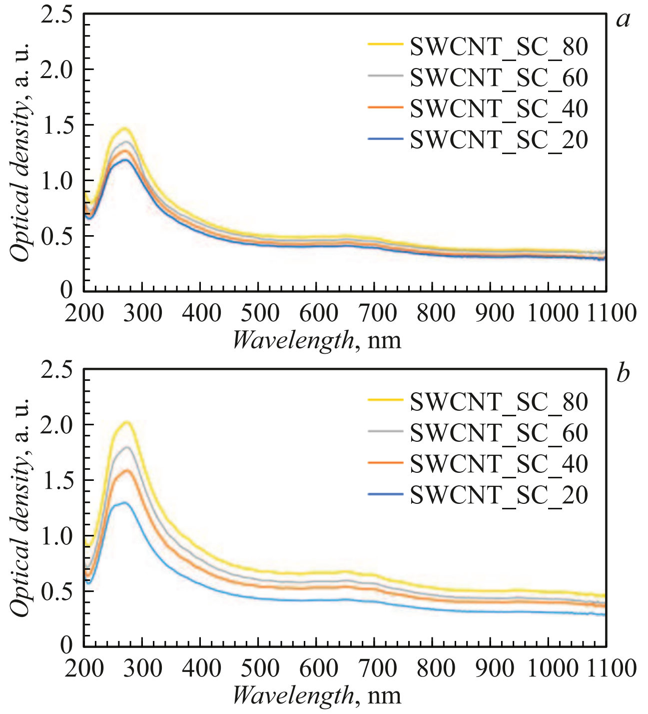

Figure 2. Absorption spectra of the carbon dispersion media in the presence of: *a* — SC surfactant, *b* — DOC surfactant at various duration of the ultrasonic treatment.

electronics, in particular, for the manufacture of electrodes and functional elements of sensor systems, was discussed.

2.1. Effect of ultrasonic homogenization time on optical properties of dispersed media

In section 2.1 of this paper, the effect of the long-term ultrasonic homogenization on the optical properties and degree of dispersion of SWCNT in colloidal systems stabilized with SC and DOC surfactants was investigated.

Fig. 2 shows optical absorption spectra of the dispersed media of SWCNT_SC (Fig. 2, *a*) and SWCNT_DOC (Fig. 2, *b*) at different duration of ultrasonic treatment (20, 40, 60 and 80,min). As the treatment time increases, the intensity of the absorption band rises in ~ 270 nm region, corresponding to $\pi - \pi^*$ transitions in the nanotube structure. This effect indicates gradual destruction of large agglomerates and higher degree of particle dispersion in the volume of the solution.

The most distinct changes were registered for the medium with DOC: optical density of SWCNT_DOC dispersions during a 80 min treatment exceeded the values for SWCNT_SC approximately by 25 %–30 %. This indicates a more effective interaction of DOC with the surface of nanotubes and its ability to provide a stable colloidal system. After 80 min of ultrasonic exposure, the spectral characteristics stabilized, which makes it possible to consider this mode optimal in terms of the degree of dispersion.

To confirm the observed trends, a DLS analysis was performed. The data obtained showed that with longer periods of ultrasonic homogenization, the average hydrodynamic radius of the particles decreased, and the proportion of the fine fraction became larger (Table 1). Thus, for DOC-based samples the proportion of scattering from fine particles amounted ~ 85 % at 80 min, while for the systems with SC it was no higher than ~ 60 %.

The results of spectral analysis and measurements by the DLS method demonstrate a consistent trend: longer ultrasonic treatment time contributes to the destruction of nanotube agglomerates and higher uniformity of dispersions. At the same time, the use of DOC provides a higher degree of stabilization and uniformity of the distribution of nanotubes compared with SC.

Table 1. Results of measurement of the dispersed medium samples with SC and DOC surfactants by DLS method at different duration of ultrasonic treatment

Duration of ultrasonic treatment, min	SC		DOC	
	Scattering portion in sample, %	Average radius, nm	Scattering portion in sample, %	Average radius, nm
20	31	351	58	214
	69	48 000	42	31 000
40	42	286	67	178
	58	44 000	33	27 000
60	55	245	80	169
	45	25 000	20	22 000
80	63	200	86	142
	37	21 000	14	18 000

2.2. Effect of centrifugation time and power on optical properties of dispersed media

Optical spectra of SWCNT-based dispersed media with the addition of DOC surfactants treated with ultrasound for 80 min were obtained (Fig. 3). The spectra demonstrate the dependence of the optical density of SWCNT/DOC dispersions over a wide spectral range on the centrifugation rate, which varies from 100 to 3500 rpm at a fixed centrifugation time of 30 min.

Optical density analysis showed that an increase in the centrifugation rate resulted in a slight decline of optical density, while the overall change did not exceed $\sim 2\%$. This may indicate a high kinetic stability of the studied dispersions, since stochastic aggregation and sedimentation of particles are minimal under such conditions. Maintaining an almost constant optical density of the filler liquid indicates a high degree of dispersion and the absence of significant coagulation or precipitation processes within the studied centrifugation conditions.

The results of DLS for dispersed SWCNT media with DOC surfactants, treated with ultrasound and subjected to centrifugation at various rotor speeds for 30 min, are presented in Table 2. According to DLS, two fractions of particles are distinguished: predominant (86%–87%) with an average radius of 139–143 nm and a less pronounced one (13%–14%) with a radius about 18000 nm. When the centrifugation rate changes from 0 to 3500 rpm, stability of the percentage ratio of both fractions and their sizes is observed.

Analysis of these data shows that the growth of centrifugation rate has virtually no effect on either the particle distribution or their average size. The difference in the radius of dispersed nanoparticles is less than 2% within the studied rates. This stability of coarse-grained fraction and nano fraction is consistent with the results of optical spectroscopy, where it was shown that the samples' optical density remained virtually unchanged with variation of centrifugation parameters. These data combined prove the high kinetic stability of dispersed media: even with a higher rate of centrifugation, the aggregative processes and precipitation of large particles do not rise, and the fine-dispersed fraction of SWCNT retains its characteristics.

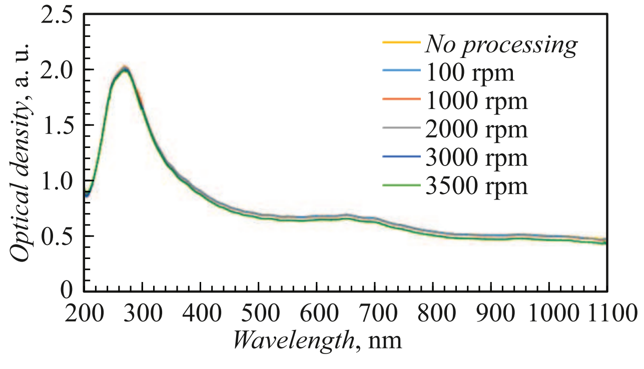

Figure 3. SWCNT_DOC dispersed media spectra versus centrifugation speed.

Table 2. Results of measurement of the dispersed medium samples with DOC surfactant by DLS method at different speed of centrifugation (duration of 30 min)

Rate of centrifugation, rpm	Scattering proportion in a sample, %	Average radius, nm
0	86	142
	14	18 000
100	85	140
	15	18 000
1000	86	143
	14	18 000
2000	87	139
	13	18 000
3000	86	140
	14	18 000
3500	87	138
	13	18 000

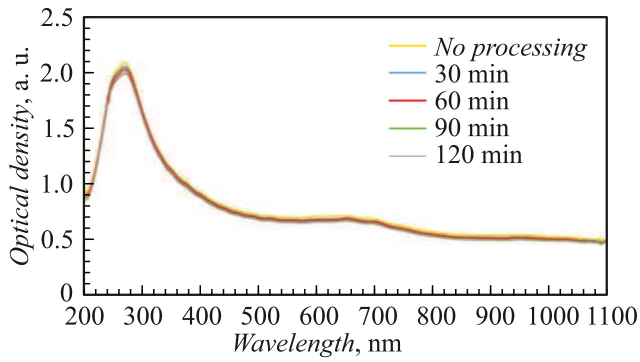

Figure 4. SWCNT_DOC dispersion media spectra versus centrifugation time.

Further, the dispersed media of SWCNT with DOC surfactant, pretreated with ultrasound 80 min, were subjected to centrifugation for various periods (30, 60, 90, 120 min). At that, the centrifugation rate remains constant. To assess the changes, optical density spectra of the filler liquid were studied over the entire wavelength range (200–1100 nm) (Fig. 4).

The analysis of the spectra showed a gradual decline in optical density with increasing centrifugation time. The greatest changes are observed during the first 90 min, after which the spectrum parameters stabilize: at processing times of 90 and 120 min, no any significant changes are registered.

Table 3. DLS data of measuring the dispersion media samples with DOC surfactant at various centrifugation times (rotor speed 3500 rpm)

Time of centrifugation, min	Proportion of scattering in sample, %	Average radius, nm
0	86	142
	14	18 000
30	88	139
	12	17 500
60	89	137
	11	17 000
90	90	134
	10	16 500
120	90	134
	10	16 500

DLS data (Table 3) with a fixed maximum centrifugation rate and varying treatment times (from 0 to 120 min) show that in the first 90min, the proportion of the fine fraction rises (from 86 % to 90 %), and its average radius declines (from 142 to 134 nm). The proportion of coarse aggregates, on the contrary, becomes smaller, and their size goes down from 18 000 to ~ 16 500 nm. After 90 min, the parameters stabilize: a further increase in time does not lead to significant changes in the fraction and particle size.

This phenomenon can be explained by the fact that in the first minutes of centrifugation, large aggregates predominantly precipitate, resulting in enrichment of the supernatant with a fine fraction and to the purification of the dispersion from large particles. Such kinetic behavior is typical for colloidal systems, centrifugation promotes separation by size, and the stability of the fine-dispersed phase rises until an equilibrium is reached between settling and stability of suspended particles.

Thus, the stability of optical properties and dimensions after a 90 min period indicates the formation of a system with high kinetic stability, where particles are retained in suspension due to the action of surfactants and steric/electrostatic stabilization mechanisms.

2.3. Influence of homogenization and surfactant parameters on electrical characteristics of coatings on titanium surface

SWCNT and surfactant carbon coatings were formed by spray deposition onto pre-prepared titanium substrates acting as a model of a medical device. A detailed description of substrates preparation and application of coatings is given in the corresponding section 1.4. After the coatings were obtained, the specific electrical conductivity of the samples (S/m) was measured to quantify the electrical properties, and the results were compared with the electrical conductivity of the native titanium surface. The tests were carried out for coatings formed by SWCNT dispersions with various surfactants in conditions of varying ultrasonic homogenization time (20, 40, 60 and 80 min). The obtained results are shown in Fig. 5, which demonstrates the dependence of the conductivity of titanium plates with various coatings applied on the treatment time: 20, 40, 60, and 80 min.

The conductivity of a titanium substrate makes $10.19 \cdot 10^3$ S/m, which is much less than the values obtained for CNT- and surfactant-based coatings. For the media containing sodium cholate (SWCNT_SC)) a gradual rise of conductivity from $14.23 \cdot 10^3$ S/m after 20 min treatment to $36.14 \cdot 10^3$ S/m after 80 min treatment is observed. In contrast to this, the samples obtained from the dispersion media based on sodium deoxycholate (SWCNT_DOC), demonstrated a significant growth of conductivity — from $22.58 \cdot 10^3$ S/m after 20 min treatment to $155.79 \cdot 10^3$ S/m after 80 min. Already after 40 min of treatment, the conductivity of coatings with DOC ($41.73 \cdot 10^3$ S/m) exceeded the maximum values of the system with SC, which indicates a fundamentally more efficient dispersion and structuring of nanotubes when using this surfactant.

The maximum conductivity achieved for a coating based on SWCNT-DOC is approximately 4.3 times higher than that of a medium with SWCNT_SC, whereas conductivity of an unmodified titanium substrate is more than 15 times higher. Such a significant increase is due to the formation of a spatially developed conductive CNT grid evenly distributed in the surface layer of titanium. DOC molecules contribute to a more complete opening of the nanotube bundles and prevent their reaggregation, which leads to an optimal three-dimensional percolation structure providing high conductivity.

The results obtained demonstrate the advantages of using DOC as a dispersing agent in the formation of carbon coatings on titanium substrates. The use of this surfactant ensures formation of highly homogeneous and electrically

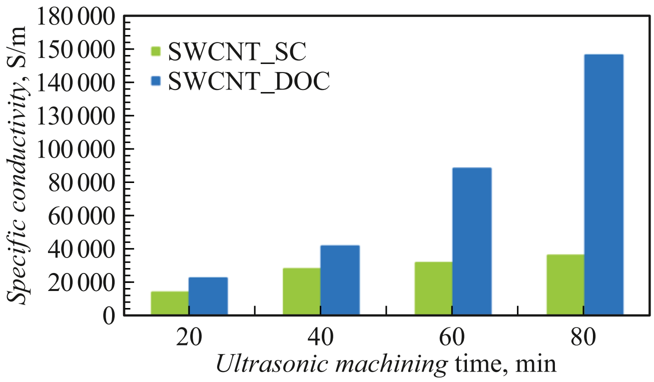

Figure 5. Solid samples conductivity versus ultrasonic treatment time: green — coating based on SWCNT_SC dispersion medium; blue — coating based on SWCNT_DOC dispersion medium.

conductive structures, making this approach promising for the development of biomedical devices with improved electrophysical properties.

3. Prospects of further research

The obtained results on optimization of SWCNT dispersed media prepare a basis for further research aimed at formation of TiC carbide coatings by laser treatment of carbon layers on titanium. In the long term, it is necessary to find the effect of the carbon coatings uniformity and the degree of dispersion of nanotubes on the effectiveness of laser-induced TiC formation, as well as to determine the relationship between the parameters of laser exposure and the structural, mechanical and electrophysical properties of the formed layers.

Special attention should be paid to studying the mechanisms of carbon diffusion, depth of TiC phase formation, and adhesion of carbide layer to the substrate. An additional task is to assess the stability of TiC coatings in conditions simulating operation in biomedical devices. These studies will improve the technology for creating conductive and durable composite coatings for titanium electrodes.

Conclusion

In the course of research, a method for modifying a titanium surface for biomedical electronics was developed and improved, based on the formation of conductive coatings consisting of SWCNT stabilized with surfactants.

The parameters of ultrasonic homogenization and centrifugation were found to be the key factors influencing the quality of dispersed media and subsequent electrophysical properties of coatings. Optical spectroscopy and DLS methods have shown that an increase in the ultrasonic treatment time to 80 min leads to significant destruction of SWCNT agglomerates, smaller average hydrodynamic radius of particles and higher dispersions uniformity. At the same time, the use of DOC as a surfactant demonstrated an advantage over SC in terms of stabilization efficiency, which was expressed in higher optical density and the proportion of the fine fraction (up to 86 %).

The superiority of DOC surfactants compared to SC surfactants is explained by differences in their amphiphilic properties, which are directly related to the chemical structure of the molecules. DOC molecule contains fewer hydroxyl groups than SC, which gives it a more pronounced hydrophobicity. This quality enhances the interaction of DOC with carbon surfaces, in particular due to hydrophobic interactions and $\pi-\pi$ bonds between the flat sections of DOC molecule and the surface of graphene-like nanotubes. The flatter and more compact conformation of DOC molecule makes the coating to stick to the nanotubes surface more tightly, forming a stable molecular shell that reliably prevents the aggregation. In addition, DOC has a negative surface charge, which contributes to significant electrostatic repulsion between the particles and, as a result, improves the dispersion of nanotubes in the medium.

The study of the centrifugation effect confirmed high kinetic stability of optimized SWCNT-DOC dispersions: variation of the rotation speed in the range of 100−3500 rpm did not cause significant changes in the particle size distribution. With an increase in the centrifugation time to 90 min, the dispersion was purified from large aggregates with a simultaneous increase in the proportion of fine fraction to 90 % and a decrease in its average radius to 134 nm, after which the system reached a stable state.

The highest conductivity of coatings formed by the sputtering method on titanium substrates was achieved using SWCNT_SC dispersed medium, treated with ultrasound for 80 min, and amounted to $155.79 \cdot 10^3$ S/m. This value is 4.3 times higher than the electrical conductivity of coatings based on SWCNT_SC and more than 15 times the conductivity of unmodified titanium. Such a significant improvement in electrophysical characteristics is due to the formation of a developed three-dimensional conductive grid of individually dispersed nanotubes, provided by the effective action of DOC.

Thus, improving the preparation of dispersed media based on SWCNT and surfactants makes it possible to obtain homogeneous and highly conductive coatings on titanium, which creates a reliable basis for subsequent laser processing in order to form composite structures of „Ti–CNT/TiC“ with specified functional properties for applications in biomedical electronics.

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Conflict of interest

The authors declare that they have no conflict of interest.

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