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Microwave absorption in carbon fibers Ural N-24 and their composites based on polyamide Phenilone C-2

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Properties of the resonance (EPR, FMR) and non-resonance microwave absorption (NMA) in carbon fibers (CFs) Ural N-24 and powder samples of Phenilone C-2 /CFs composites were studied using a 3-cm EPR spectrometer "Radiopan" SE/X-2544. It was shown that the EPR signals of carbon fibers are mainly due to free electrons. They form response as of symmetric (Lorentz shape) or asymmetric (Dyson shape) EPR line, depending on the fulfillment of the conditions: $d < \delta$ or $d > \delta$, where d is the thickness of CFs threads or bundles; δ is the skin layer thickness for a given wave frequency. The effect of a strong NMA in CFs and PhC-2 /CFs composites due to the non-resonant absorption of the microwaves by free carriers was found. It is shown that the magnitude of the NMA effect can be controlled by changing both the concentration of CFs in the composite and the density of the powder. The latter determines electrical contact between the individual particles. It is established the fact of the formation of strong ferromagnetic resonance (FMR) signals in composites. The magnitude of the FMR signal increases non-linearly with increasing of CFs concentration. To explain this effect, a model is proposed taking into account the role of the technological process of magnetic mixing of the powder accompanied by the friction of strong carbon fibers with ferromagnetic additives. The FM material's micro- and nanoparticles are split off in this process and give rise to the ferromagnetic or superparamagnetic properties of the prepared composites.

Keywords: carbon fibers, polyamide-based composites, electron paramagnetic resonance, nonresonant microwave absorption

Мікрохвильове поглинання в вуглецевих волокнах УРАЛ Н-24 та їх композитах на основі поліаміду Фенілон С-2. *А.А. Кончиць, Б.Д. Шаніна, С.В.Красновид,О.І.Буря, А.-М.В.Томіна, К.А.рьоміна*

Властивості резонансного (ЕПР, ФМР) і нерезонансного мікрохвильового поглинання (НМП) у вуглецевих волокнах (ВВ) Урал Н-24 і порошкоподібних зразках композитів Фенілон С-2 / ВВ вивчено із застосуванням радіоспектрометра 3-см діапазону Radiopan SE / X-2544. Показано, що ЕПР сигнали вуглецевих волокон обумовлено, головним чином, вільними електронами, що формують відгук у вигляді симетричної (форми Лоренца) або асиметричної (форми Дайсона) лінії ЕПР в залежності від виконання умов: $d < \delta$ або $d > \delta$, де d – товщина нитки або пучка ВВ, δ – товщина скін-шару у ВВ для даної частоти хвиль. Виявлено ефект сильного НМП уВВ і композитах ФС-2 / ВВ, обумовлений поглинанням НВЧ вільними носіями ВВ. Показано, що величиною НМП можна управляти зміною як концентрації ВВ в композиті, так і щільності порошку, від якої залежить електричний контакт між окремими порошинка-

ми. Встановлено факт формування сильних сигналів феромагнітного резонансу (ФМР) в композитах, величина яких нелінійно росте з ростом концентрації ВВ. Запропоновано модель для пояснення ефекту, що врахову роль технологічного процесу магнітного перемішування суміші, який супроводжуться тертям міцних вуглецевих волокон з феромагнітними добавками. В результаті цього процесу відщеплюються мікро- і наночастинки ФМ матеріалу, які і відповідають надалі за феромагнітні або суперпарамагнітні властивості приготованих композитів.

1. Introduction

Composite materials (CMs) based on polymers with various fillers are widely used in many fields of science and technology, as they have better physical and mechanical properties compared to the original polymers [1-3]. The purposeful synthesis of new CMs is impossible without knowledge of their structure, electrical and magnetic properties at the atomic-molecular level. In particular, it is important to control the electronic properties of base polymers, fillers, the degree of dispersion of fillers in the composite, and the mechanisms of their interaction with the polymer matrix. Among the many CMs, one of the most widely used are composites containing carbon fibers (CFs), the so-called carbon plastics [3-5]. The scope of their application is the thermal protection of spacecraft and the structural elements of satellites, the automotive industry, friction units of various mechanisms, the manufacture of sports equipment, activated hydrocarbons as effective sorbents, etc. One of the features of CFs is their turbostratic structure, in which adjacent carbon layers are rotated at some angle with respect to the normal the layer, which results in an increase in the distance between the individual layers. The magnitude of these effects depends on many factors, including the type of feedstock and the temperature of treatment of CFs [2, 5, 6]. Turbostratic graphite crystallites in carbon fibers are packed in such a way that they form layers several microns in length and about nanometers thick. Thus, although the bundles of carbon fibers are micron in diameter [2, 5, 6], it can be expected that their electronic properties and, largely, mechanical properties will be determined on a nanometer scale.

In the proximity of working electronic devices, electromagnetic waves can create electromagnetic interference phenomena (EMI). To avoid this phenomenon, sensitive devices and devices emitting undesirable and potentially harmful EM radiation must be shielded. Electronic conductive materials can serve as shields to minimize or even eliminate these interference phenomena through the reflection and absorption of EM waves [7, 8]. For this reason, the study of the microwave absorption on new CM's is necessary for evaluation their shielding ability. The study of the resonance absorption properties permits the description of the characteristics of conduction electrons and highlights the possible contribution of the localized electrons that exist in graphitic layers as the dangle carbon bonds. The width of the EPR signals of CFs ΔB can be a source of knowledge about the imperfections of the fiber structure. In addition, magnetic resonance can also shed light on some details of the technological process of obtaining composites. The process of magnetic mixing which allows one to achieve high uniformity in the distribution of fillers in the polymer matrix results in the presence of the ferromagnetic nanoparticles in CM's. The latter can be studied by means the ferromagnetic resonance.

In this work, the magnetic resonance properties (ferro- and paramagnetic) of carbon fibers of the type Ural N-24 and their composites based on aromatic polyamide Phenilone C-2 (PhC-2) which is analogous to Nomex, are studied. The experiments were carried out at room temperatures on a 3-cm "Radiopan" SE/X-2544 EPR spectrometer with a magnetic field modulation of 100 kHz. The purpose of this work was to study the properties of resonant and non-resonant microwave absorption of carbon fibers and composites PhC-2 / CFs, as well as the dependence of these properties on the composition of the composite, dispersion of fillers, the state of the defect subsystem, and the mechanisms of interaction between the matrix and the filler.

2. Experimentals

Aromatic polyamides are perspective polymer materials that combine a high level of physic-mechanical and thermophysical properties. That's why the aromatic polyamide phenylone C-2 (TU 6-05-221-226-72) was chosen as a binder. It is white-colored finely dispersed powder with a bulk density of 0.2 – 0.4 g/cm^3. Phenylone is one of the few materials that maintain the per-

Table 1. Properties of carbon fibers Ural N-24.

The number of filaments per thread	Thread color	Density, g/cm^3	The limit of compressive strength, MPa	Modulus of elasticity, GPa
6600	black	1.71	1500	80÷100

formance of pneumatic and hydro automatic joints operated in harsh conditions. Carbon fibers Ural N-24 (TU 6-06-11-124-85) were used as a filler, the advantages of which are high heat resistance and strength, 2-3 times higher than the strength of conventional chemical fibers. Preparation of compositions based on phenylone C- 2 were carried out by the method of dry mixing in the machine with the rotating electromagnetic field (0.12 T) with the help of ferromagnetic particles that were magnetically separated from the prepared composition. The prepared mixture was tableted at a room temperature and pressure of 30 MPa.

Before forming the composite, the mixture was thoroughly dried in an SPT-200 scallop oven for 2-3 hours at a temperature of 473-523 K. Next, the material was loaded into a mold heated to 523 K, heated without pressure to 598 K, and kept for 10 minutes. Then another 10 minutes under a pressure of 40 MPa at the same temperature. Next, the product was cooled at constant pressure to a temperature of 523 K, after which the pressure was removed.

The magnetic properties were studied on composite powder samples, which made it possible to study the properties of resonant (EPR and FMR) and nonresonant microwave absorption (NMA) depending on the density of the powder. Reducing the density of the powder made it possible to reduce the NMA, the large value of which prevents the observation of resonant signals due to a drastic decrease in the quality factor Q of the spectrometer cavity. During the experiments, it was found that the characteristics of the EPR signals caused directly by CFs are the same for both bulk and powder samples.

The $MgO:Cr^{3+}$ sample containing ~3×10^{14} spins was used as a reference. In addition, in some measurements, the EPR signal shape of the composite with CFs was compared with the EPR signal shape of the GL-2 silver-graphite powder (TU 5279-74).

3. Results and discussion

At the first stage of this work, the magnetic resonance properties of Ural N-24 carbon fibers were studied. Their mechanical properties are given in Table 1 [2].

For the enhancement of the EPR signal, the measurements were done for five bundles separated each from other in order to reduce the NMA effect. The diameter d of a single bundle is about 3 mm, and the length is 5 mm. On the other hand, one elementary thread of CF has a diameter *dsub* about 10^{-4}cm, i.e. one bundle contains about some thousands of threads. The geometry of the EPR experiment was the same as in [9], which made it possible to measure the EPR characteristics when the magnetic field was directed both along and perpendicular to the fiber axis.

The theory of spin resonance of conduction electrons (CESR) is developed in detail in references [10-13]. The shape of the CESR line is determined by the ratio of the skin depth, the sample thickness d, and the electron means free path δ_d during the electron spin relaxation time T_2. In the case of $(\delta/d) < 1$, an asymmetric (Dyson form) signal is observed. The ratio $(\delta/\delta_{d)}$ is responsible for the shape of the CESR line, namely, the value of the ratio of the signal amplitude in the maximum to the signal amplitude in the minimum, the line width peak-to-peak, and width of low-field wing Δ_1.

Fig. 1 shows the spin resonance spectrum of bundles of Ural-24 CFs filaments. It can be seen that the spectrum is a single asymmetric line of Dyson's shape, which is typical for the EPR signals of conducting samples in the case of skin layer depth $\delta < d$ (d is the sample thickness; in this work, d is the diameter of the bundle in Fig. 1 or the filament diameter in Fig. 2). Parameters of such spectra are described using the theory of spin resonance of conduction electrons (CESR) developed in [10-13].

The CESR spectrum of CFs bundles calculated with the found value of $(\delta/\delta_{d)}$ on the basis of theory [10-13] (Fig. 1, the right scale) describes well the experiment with the parameters:

$g = 2.0034\pm2\times10^{-4}$; $\Delta B_{pp} = 2.07$ mT;

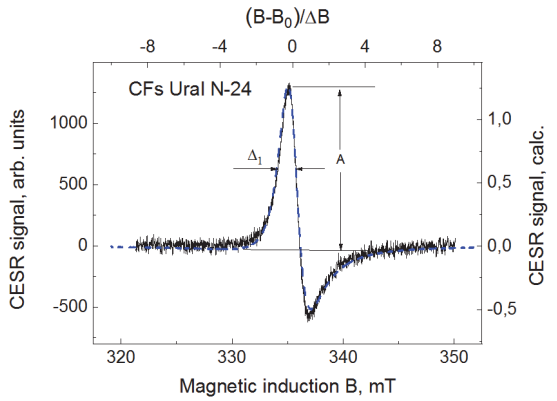

Fig 1. CESR spectrum of the Ural-24 CFs bundles. The dashed line is the simulated spectrum in dimensionless units, constructed according to the theory [10-13], with the parameters given in the text. ν = 9406 MHz.

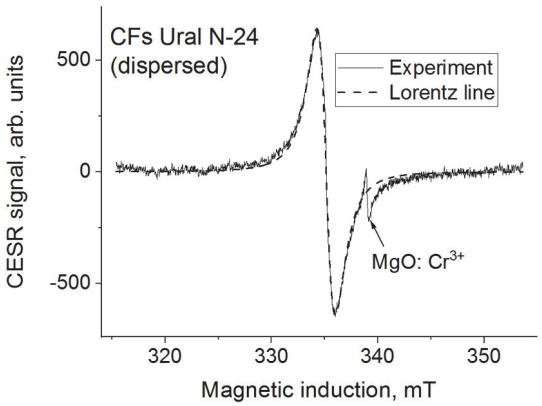

Fig 2. CESR spectrum of separated threads Ural N-24. The dotted line is the Lorentz fitting curve. ν = 9395.8 MHz.

R = 50, where $R = (\delta/\delta_d)^2$; $\delta_d = v_d T_2$. The electron spin relaxation time T2 is found from the value

$$\Gamma = g\beta\Delta_1 \cdot T_2, \qquad (1)$$

where Δ_1 is a line width of the left wing of the signal and is equal to 1.4 mT (see Fig. 1), Γ value is found from the dependence $\Gamma(\delta/\delta_d)$ obtained in [9]. For $\delta/\delta_d = 7$ value Γ = 1, so that from (1) we have $T_2 = 3\cdot10^{-9}$ s. At room temperature we can suppose that the free-electron velocity in the thread of CF is equal thermal velocity $v = (kT/me)^{1/2} = 6\cdot10^6$ cm/s, therefore in the bundle, the electron velocity is less $v_d < 6\cdot10^6$ cm/s. Finally, the obtained values are $\delta_d < 0.018$ cm, $\delta < 0.126$ cm $< d = 0.5$ cm. The fact $\delta < d$ says about the existence of the electron motion from the thread to the neighbor thread.

It is also known [10, 11] that in the case when the thickness of the conductive sample is less than the depth of the skin layer for a given microwave frequency, the CESR line is symmetrized and takes the usual Lorentz shape. Indeed, when the above bundle of CF was divided into the separate individual threads several microns thick then the threads were crushed and dispersed in paraffin, the CESR line becomes symmetrical and takes on the Lorentz shape (Fig. 2).

The parameters of the CESR line in Fig. 2 are as follows:

$g = 2.0030\pm2\times10^{-4}$, $\Delta B_{pp} = 1.8$ mT.

The comparison of the data in Fig. 1 and Fig. 2 shows that the g factors of the lines in Fig. 1 and Fig. 2 are slightly different.

We also noted that the quality factor Q of the microwave resonator decreases strongly in the presence of carbon fibers due to non-resonant microwave absorption (NMA) by free carriers, which are present in CFs, as a result, amplitudes of all resonance signals decrease. This fact was clearly recorded by the change in the EPR signal of the reference sample, which depends only on the change in Q, and is unrelated to a change in the ratio between the values of d, δ and δ_d for CFs and composites.

Thereafter the EPR spectrum of the Phenilon PhC-2 powder sample without fillers is shown in Fig. 3.

The parameters of the spectrum shown in Fig. 3, the following: $g = 2.0037 + 2\times10^{-4}$; $\delta B_{pp} = 0.9$ mT. As expected, these parameters coincide with those for bulk PhC-2 samples, and the signals themselves are caused by defects in the PhC-2 polymer chains [14].

Microwave absorption in composite samples of PhC-2/CFs is more complex. In comparison with the initial polymer, the intensity of ferromagnetic (FM) signals substantially increases due to the presence of micro- and nanoparticles of iron oxides as an integral component of the technological process of preparing a composite, including magnetic mixing of the initial powder. Fig. 4 (spectrum I) shows the spectrum of magnetic resonance absorption of the initial composite powder PhC-2 + 40 wt.% CFs.

The broad lines of magnetic resonance in Fig. 4 (spectrum I) contain signals from FM

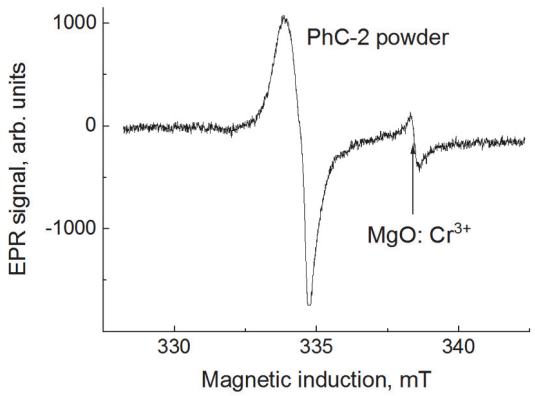

Fig. 3. EPR spectrum of the powder sample PheniloneC-2. The signal on the right belongs to the MgO:Cr^{3+} reference sample.

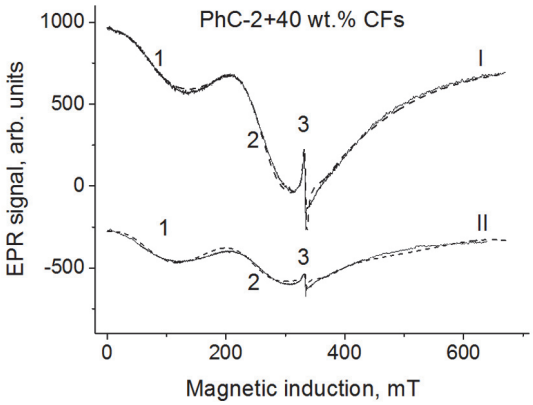

Fig 4. The EPR spectra in the powder of the composite PhC-2/40 wt.% CFs. Spectrum I is a powder freely poured into a quartz tube. Spectrum II is the same powder, but slightly compressed. Dotted lines are simulated spectra with the parameters given in the text.

nanoclusters. These are signals 1 and 2, which are characterized by the parameters: $B_{res,1}$ = 70 mT, $\Delta B_{pp,1}$ = 208 mT; $B_{res,2}$ = 260 mT, $\Delta B_{pp,2}$ = 138 mT. They relate to clusters whose magnetic moment M is oriented parallel and perpendicular to the applied magnetic field B, respectively. Line 3 at the center of the spectrum with $B_{res,3}$ = 334 mT belongs to conduction electrons in graphite-like structures of carbon fibers. The wide background line in the region of high magnetic fields (described as the part of the Lorentz line) has an unknown nature.

Spectrum II in Fig. 4, recorded under conditions of insignificant compression of the powder (~ 200 g/cm^2), is similar to spectrum I, but the amplitude of signals 2, 3 and the background signal decreased by ~ 3 times, and the amplitude of signal 1 decreased by ~ 1.5 times. It was established that the effect of decreasing resonance signals is associated with an additional decrease in the Q factor of the resonator of the spectrometer due to the NMA effect, which increases even with slight powder compression. Under more severe compression, when the initial bulk volume of the powder in the quartz tube decreases by a factor of 1.5-2, the registration of EPR signals becomes impossible due to a drastic drop in Q due to the NMA.

The EPR spectrum of CFs in the composite, shown in Fig. 5 (curve 1), is recorded in a narrower interval of the magnetic field B scanning. The spectra of micro graphite powder freely poured into a quartz tube (curve 2) and the same powder dispersed in paraffin (curve 3) are provided for comparison.

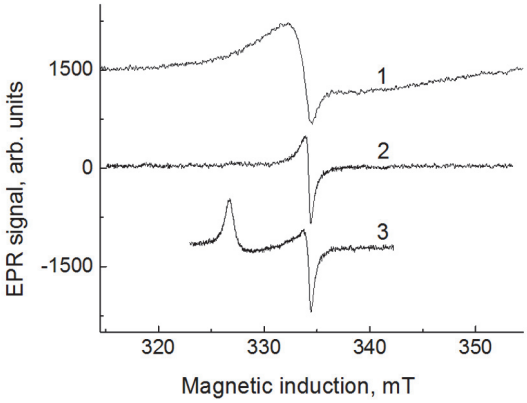

Fig. 5. The central part of the EPR spectrum of the composite PhC-2/40wt.% CFs (curve 1). Curves (2) and (3) show the EPR spectra of micro graphite powder freely poured and dispersed in paraffin, respectively [15].

The EPR spectrum of CFs in a composite PhC-2/30 wt.% CFs with a lower content of fibers has a slightly different form (Fig. 6).

The EPR spectrum in Fig. 6 consists of two lines L1 and L2, caused by CFs and defects in polymer chains, respectively. For both lines, their characteristic parameters are determined. Line L1:

$g = 2.0030 \pm 4 \times 10^{-4}$, ΔB_{pp} = 9.2 mT.

The parameters of the L2 line remain the same as in pure PhC-2: $g = 2.0038 \pm 2 \times 10^{-4}$, ΔB_{pp} = 1.0 mT. In contrast to the composite PhC-2/40 wt.% CFs (see Fig. 4), in composites with a lower fiber content PhC-2/30 wt.% CFs (Fig. 6) and PhC-2/20 wt.% CFs (spectrum not presented), the effect of the

Table 2. The intensity and linewidths of the magnetic resonance signals in powder composites with different contents of carbon fibers.

CFs content, wt.%	20	30	40	50
$I_{CFs(1)}$ *), a.u.	14	21	35	~46
$\Delta B_{CFs(1)}$, mT	7.1	9.2	~9	2; 15
$I_{FeOx(1)}$ **)	a.u.	850	1100	4450
$\Delta B_{FeOx(1)}$, mT	94	98	110	107
$I_{CFs(1)}/I_{CFs(2)}$, $I_{FeOx(1)}/I_{FeOx(2)}$	~1	~1	0.5	0.76

*) The designations "1" and "2" refer to freely poured and slightly compressed powder, respectively.
**) The data refer to FMR line 2 in Fig. 4, which was interpreted the most accurately.

NMA is weaker and does not change with light compression of the powder. Table 2 presents the intensity and linewidth of the EPR and FMR signals origin from carbon fibers and FeOx nanoclusters, respectively, in composites with different CFs content.

The physicochemical properties of carbon fibers and composites with their participation are the subject of numerous studies [1-6, 16-21]. It is known that at relatively low temperatures of CFs treatment ($T_{HTT} \leq$ 1750C), the so-called carbonized fibers are formed. The properties of bulk graphite structures in such CFs are practically not manifested, and, accordingly, the anisotropy of the g-factor, inherent to graphite, in the ESR spectra of CFs is absent [9, 22]. The anisotropy of the g factor begins to manifest itself and gradually increase with the growth of T_{HTT} up to $T_{HTT} \approx$ 3000C [9, 17, 22]. However, even at such high T_{HTT} values, the maximum value of the CFs g-factor when the magnetic field H is parallel to the c axis (normal to the graphite plane) does not reach g = 2.050 for perfect graphite [25], remaining at the level $g_3 \equiv g_{||} = 2.028$ [16]. This is due both to the turbostratic structure of the CFs and to the greater than in graphite interplanar distance, so as scatter of the directions of the c axes of the graphite planes with respect to the chosen direction of the magnetic field [5, 16, 22, 26, 27]. In addition, the effects of transversemotional averaging and the interaction of free electrons with localized paramagnetic centers depending on the size of the graphite domains [9, 13, 17, 28-30] affect the measured g-factor and the EPR line width.

The value of the g-factor of the Ural N-24 carbon fibers EPR signals measured by us (Fig. 1 and Fig. 2) g = 2.0030 – 2.0034 is typical for carbon materials, including nanostructured, with defects such

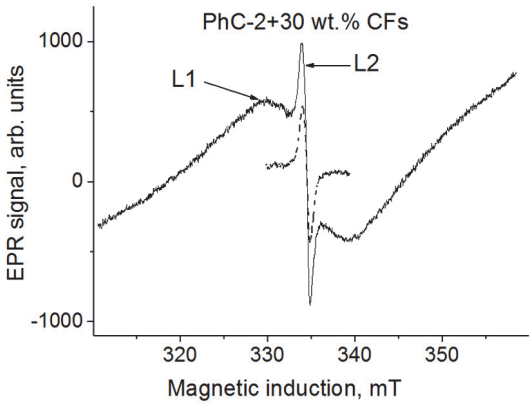

Fig 6. The central part of the EPR spectrum of the PhC-2/30 wt.% CFs composite. The spectra of freely poured and slightly compressed powder do not differ. For comparison, the dotted line shows the EPR line in the PhC-2 polymer without CFs. ν = 9382 MHz.

as dangling carbon bonds [9, 31, 32]. Conductivity in such materials, including CFs, is provided by free electrons, pseudo-free electrons in the tails of the density of states [31, 32], and thermal excitation of electrons with overcoming the potential barrier for hopping between grains [21]. As the THTT temperature increases, 3D graphite clusters are formed in the CFs [22], the conductivity of which is often described in the two-band model [26], including with the introduction of such a parameter as "relative graphite order" [33]. For the Ural-24 CFs, the value of $T_{HTT} \approx$ 2200C and, therefore, we can expect only a small anisotropy of the g-factor. The absence of experimentally apparent anisotropy of the g-factor of CFs corresponds to that expected for such a relatively low THTT.

Less obvious are the mechanisms of the formation of the EPR linewidth of CFs in composite samples, including the question of the presence of g-factor anisotropy. In-

deed, as can be seen from Fig. 1, Fig. 2, and Table 2, the width of the EPR line of CFs in composites (ΔB_{CFs} = 7÷15 mT) significantly exceeds its value for separately measured CFs (ΔB_{CFs} = 1.8÷2.1 mT). In the PhC-2/40 wt.% CFs composite, the shape of the EPR line caused by CFs (Fig. 5, curve 1) is characterized by the presence of a wide shoulder in its low-field part. Such line shape is typical for microdispersed graphite powders (Fig. 5, curve 2, see also [34]), where it is due to anisotropy of the g-factor in graphite. In composites containing 20 and 30 wt.% CFs, the shape of the CFs line is close to Lorentz shape. This is also true for a composite with 50% CFs, but there the central part of magnetic resonance spectrum consists of two lines: narrow ($\Delta B \approx 2$ mT) and wide ($\Delta B \approx 15$ mT) (see Table 2). The large EPR line width of the CFs lines in these composites and their shape close to Lorentz shape can be explained by the broadening effect due to magnetic fields of the ferro- and superparamagnetic particles, whose role increases with increasing CFs content in the composite (see IFeOx (1) values in Table 2). The mechanism of the formation of the EPR linewidth of CFs in a composite with 40 wt.% CFs content is still unclear and requires further study. However, in any case, it is necessary to take into account the fact that a "frozen" chaotic spatial distribution of the CFs takes place in the composites, which means the scatter of their orientations in relation to the direction of the external magnetic field. The presence of the anisotropy of the g factor of the CFs leads to an increase in the total width of the spectrum, as is the case in graphite.

Carbon fibers containing graphite domains in the free state can also line up in an external magnetic field similarly to micro graphite powders [15] due to the rotational moment resulting from the anisotropy of diamagnetism in graphite [22, 35, 36]. This means that the EPR spectrum of the CFs in Fig. 1 may be related to partially oriented CFs.

As already noted, a strong NMA signal is observed in CFs samples and PhC-2 / CFs composites due to the presence of conductive electrons in carbon fibers that absorb a wide range of radio waves, including microwaves. NMA absorption in CFs bundles is very large and decreases the resonator Q factor. In order to be able to study EPR signals in them, in manycases, it is necessary to isolate the CFs threads from each other, achieving the condition d < δ, where d is the thickness of the CFs thread or bundle, δ is the skin layer thickness for given wave frequency [9, 33]. For bulk samples of PhC-2/CFs composites, the possibility of electrical contact between the CFs depends on the concentration of the CFs and the uniformity of their distribution in the composite. For the powder samples of the composites studied in this work, the size of individual powder particles and the density of their filling in the quartz tube also play a role. All of the above conditions affect the magnitude of the NMA in the samples of composites. With a decrease in the concentration of carbon fibers and/or extent of the powder grinding, the conditions for the realization of electrical contact between CFs are declining, which confirms the comparison of the behavior of the signals in Fig. 4 and Fig. 6.

The clearly observed correlation between the percentage of CFs in the composite and the intensity of the FMR signals (see Table 2) is surprising at first glance. Moreover, Table 2 shows that there is a non-linear increase in the intensity of FMR signals with an increase in the content of CFs. This phenomenon can be explained by the fact that the technological process of magnetic mixing of the powder for the obtaining a uniform distribution of CFs in the composite is accompanied by the friction of strong carbon fibers with ferromagnetic additives. As a result, micro- and nanoparticles of the FM material split off and remain in the mixture. The latter is responsible for the ferromagnetic and/or superparamagnetic properties of the prepared composite samples. The efficiency of such processes increases significantly with increasing CFs content in the composite.

4. Conclusion

1. Ural N-24 viscose carbon fibers processed at "medium" temperatures T_{HTT}≈2200C show microwave properties inherent to both carbonized and graphitized materials. The EPR signals of the CFs are caused by conducting electrons in the CFs structure. The symmetric (Lorentz shape) or asymmetric (Dyson shape) EPR line is observed depending on the condition of the fulfillment d<< δ or d >> δ, where d is the thickness of the filament or bundle of CFS, δ is the thickness of the skin layer for a given frequency of microwaves. Taking into account of these features allows us not only to describe the characteristics of conduction

electrons, but also to ighlight the possible contribution of localized electrons, which are characterized by the s ymmetrical EPR signal.

2. The theoretical modeling was carried out for all observed magnetic resonance signals. It was shown that the main parameter determining the characteristics of the observed Dyson shape EPR signals is the parameter $R = T_D/T_2$, where T_D is the electron diffusion time through the skin layer, T_2 is the electron spin relaxation time. Value R = 50 for CFs Ural N-24 was obtained. Since the width of the EPR lines of CFs ?B and the value of the parameter R obviously depend on the perfection of the fiber structure, the obtained data can be used for forecasting not only electronic but also mechanical properties of various types of CFs and composites with their participation.

3. In addition to resonant signals, the electronic subsystem of carriers, due to the semiconductor behavior of CFs, is characterized by a large non-resonant microwave absorption. Both a change in the concentration of CFs in the composite and the density of the powder can control the magnitude of the NMA in powdery composites with CFs. This opens up the possibility, in addition to the main function of these composites (tribological applications), simultaneously to realize microwave shielding tasks.

4. In the technology for producing composites used here, an important role is played by the process of magnetic mixing of the powder, which allows one to achieve high uniformity of the distribution of the fillers in the polymer matrix. The friction of strong CFs with ferromagnetic additives accompanies this process. As a result, the micro- and nanoparticles of the FM material are split off and become responsible for the ferromagnetic properties of the prepared composites. A characteristic feature of this process is a non-linear increase in the intensity of FMR signals with an increase in the CFs concentration.

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