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The structuring of tribotechnical epoxy composite materials in the electromagnetic field

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The influence of the cyclic processing mode on the structure formation of highly filled epoxy resin based press-composites in the field of ultrahigh-frequency currents has been established. As a result of this processing, the duration of the structuring process has been shortened and high physical, mechanical and tribotechnical characteristics of the epoxy composites have been obtained. The optimum number of heating and cooling cycles, and duration of these cycles have been defined; the structure formation features of the epoxy composites under the cycle influence of electromagnetic radiation has been revealed. The microstructure of the press-composites has been studied. Recommendations for the technological process of forming the tribotechnical products based on epoxy composite materials are given.
Keywords: cyclic mode, treatment time, cooling, destruction, fillers, strength, fracture surface, wear intensity.

Определено влияние циклического режима обработки композиций на основе эпоксидной смолы на процессы структурирования высоконаполненных пресскомпозитов в поле токов сверхвысоких частот. В результате данной обработки сокращена продолжительность процесса структурирования и обеспечены высокие физико-механические и триботехнические характеристики эпоксикомпозитов. Определены оптимальное количество циклов нагрева и охлаждения, продолжительность данных циклов и представлены особенности формирования структуры эпоксикомпозитов под циклическим воздействием электромагнитного излучения. Исследовано микроструктуру пресскомпозитов. Даны рекомендации для технологического процесса формирования триботехнических изделий на основе эпоксикомпозитных материалов.

Структурування епоксикомпозитних матеріалів триботехнічного призначення в електромагнітному полі. *П.П.Савчук, В.П.Кашицький, М.Д.Мельничук, О.Л.Садова, С.В.Мисковець*

Визначено вплив циклічного режиму обробки композицій на основі епоксидної смоли на процеси структурування високонаповнених прескомпозитів у полі струмів надвисоких частот. У результаті даної обробки скорочено тривалість процесу структурування та забезпечено високі фізико-механічні і триботехнічні характеристики епоксикомпозитів. Визначено оптимальну кількість циклів нагрівання та охолодження, тривалість даних циклів та представлено особливості формування структури епоксикомпозитів під циклічним впливом електромагнітного випромінювання. Досліджено мікроструктуру прескомпозитів. Подано рекомендаці для технологічного процесу формування триботехнічних виробів на основі епоксикомпозитних матеріалів.

1. Introduction

At present, an improvement of the physico-mechanical, thermo-physical and operational properties of polymeric composites based on the thermosetting binders is possible due to the modification of the binder polymeric mesh during structuring the system under the influence of external physical fields: ultrasonic treatment, treatment in the field of high frequency currents, laser, infrared or ultraviolet radiations. The perspective use of alternative technologies for modification of polymers is determined in some cases by the reduction of long-term classical processes of product formation, reduction of high energy costs and elimination of harmful production factors.

It is efficient to use the energy of high-frequency electromagnetic waves for intensive structuring of epoxypolymer composite materials, which are widely used for the manufacturing the tribotechnical products. Various composition filling degrees, chemical composition, phase distribution of the components, and morphological parameters of the filler particles determine the peculiarities of the structuring process of epoxy composite materials. Therefore, the determination of the parameters of the epoxy composite product formation modes in the field of high-frequency currents is of considerable scientific and practical interest.

The fundamental distinguishing feature of heating in an electromagnetic field is the release of thermal energy in the bulk of the heated material. Depending on the electrical properties of the material, two methods of heating are used: induction heating of conductive materials in a magnetic field and heating of non-conducting materials in an electric field [1, 2].

At present, the treatment of materials in the electromagnetic field is mainly used for the purpose of heat treatment of products or for drying of moist materials. In the case of polymer compositions, this treatment would result in the intensification of the structuring processes in polymer composite materials, increasing the productivity of the manufacturing process and improvement of the quality of the product.

In the process of hardening the polycomposites under convection heating, physical and chemical bonds occur between the active groups. These bonds cause the convergence of macromolecules and shrinkage of the binding agent. Between the macromolecules there are significant stresses that reduce the strength characteristics of polymer composites [1]. Therefore, the production of high-quality polymeric materials is connected with the problem of a long-term process of their hardening. Moreover, the degree of polymerization (volume fraction of the polymer mesh) usually does not exceed 85 % even with long-term convection heating, which is insufficient.

For solidification of compositions based on thermosetting polymers, electromagnetic radiation is used in two main ranges: high frequency currents (1–100 MHz) and ultra-high frequency or microwave radiation (915–2450 MHz) [1–3]. The method of heating of polymeric materials in the field of high-frequency currents is based on the fact that the polar groups and segments of the dielectric molecules placed in the alternating electric field are oriented along with the change in its polarity. Other groups and molecules, as well as thermal motion, impede the orientation. The energy consumed to overcome the obstacles dissipates in the material and heats it. The degree of heating can be adjusted with a high accuracy [4, 5].

During the heating in the field of ultra-high-frequency currents, the temperature throughout the cross section of a homogeneous material increases simultaneously and uniformly. This leads to an increase in the hardening speed in tenfold and contributes to the formation of a better quality mesh polymer structure by reducing the proportion of low molecular weight fractions and the polymer areas capable of reactions. At the same time, due to the influence of the field of a given frequency, higher electrical conductivity and thermal conductivity of the polymeric composites are achieved with significantly lower concentrations of the filler, while simultaneously maintaining mechanical strength and ensuring the durability of the material [4].

At present, there are many theoretical and practical results of using electromagnetic radiation in various technological processes of producing polymer materials. However, despite the promise of this method, its application, as a rule, is limited to the prior heating of materials and has not yet fair widely distributed for the processes of formation of thermosetting compositions and manufacturing of finished products [6, 7].

2. Experimental

Epoxy resin ED-20 and a low-temperature hardener (polyethylene polyamine) were used as initial materials. The following fillers were used to reinforce the epoxy polymers: copper oxide powder (CuO), copper powder (Cu), spherical graphite, discrete carbon fibres.

Copper, which is also a solid lubricant, is used to improve the thermophysical properties of the tribotechnical epoxy composite material. The average diameter of the copper powder particles is 30–100 μm.

The copper oxide powder performs a reinforcing function, increases the hardness and strength of the polymer system. The particles of copper oxides are spherical and, regardless of the location in the matrix, equally perceive the load. The average diameter of the particles of copper oxide powder is 60–80 μm.

Introduction of graphite in epoxy composite materials increases the stability of their sizes, chemical resistance, antifriction characteristics, heat and electrical conductivity. Graphite allows for improving the tribotechnical characteristics of the composite material without significant reducing the cohesion strength. Spherical graphite is used.

Carbon fibers have high mechanical strength and modulus of elasticity combined with low density, low impact resistance, high chemical resistance to most aggressive media. The temperature of the carbon fiber operation is in the range of −300°C to 800°C.

Prototype samples were prepared from a homogeneous composition comprising the specified components. The ED-20 epoxy resin with hardener was added by fillers pre-dried for moisture removal. The formed composition was placed into a special mold with an anti-adhesive coating.

Pre-heat treatment was carried out in a drying oven for 0.5–1 h. The treatment in the electromagnetic field was performed to intensify the process of structuring the epoxy composites.

The structuring of the epoxy composites lasted for 24 h under normal conditions, followed by a heat treatment in stepwise mode: 50°C and 100°C with exposure for 1 h, followed by 120°C with exposure for 4 h.

The compressive strength was determined by GOST 4651-82. The samples in the form of cylinders with a diameter of 10±0.5 mm and a height of 15 mm were compressed with a surface approach speed of 2 mm/min.

Determination of wear resistance was carried in a friction machine SMC-2 using the "disk — block" scheme in dry friction conditions. The sample was mounted on the cylindrical surface of a metal counter body which rotated with a given speed. The counter body was made from steel 45 (GOST 1050-74) in the form of a disk with a diameter of 50 mm; the surface roughness was $R_a = 3.2$. The samples with a quadratic 10×10 mm^2 cross-section and a height of 15 mm were made of a monolithic material. The mass of the samples was determined on analytical laboratory scales of the type AVIV S / 3-3 with an accuracy of 0.0001 g.

The microstructure of a tribosurface of the epoxy composites was studied using a scanning electron microscope (EVO 50).

3. Results and discussion

The classical technology of structuring of epoxy composites with the use of cold-action hardeners consists in the formation of chemical bonds between components at room temperature. In these conditions, a polymer mesh with minimal residual stresses is formed, but the degree of structuring needs to be increased by the subsequent thermal treatment. As a result, the technological process of forming the products based on epoxy composites is long-lasting and energy-consuming. The use of electromagnetic radiation energy for the treatment of the compositions without exposure at room temperature allows for intensifying the structuring process simultaneously throughout the entire volume of the epoxy composite sample and to increase the productivity of the technological process of manufacturing products on their basis.

In order to made qualitative products, a special approach is needed, which consists in cyclic treatment of epoxy compositions in the field of ultrahigh-frequency currents. However, in the case of excessive energy of the electromagnetic field, the temperature of the composite increases resulting in boiling of oligomers and intensive structuring. This leads to the formation of a foamy structure that is defective and reduces the strength of the polymeric composition. Therefore, after heating under the electromagnetic treatment, it is necessary to cool the epoxy composite for the removal of excessive heat energy and the formation of chemical bonds uniformly distributed over the volume of the material. Therefore, in order to develop a technological process for formation of products based on epoxy composites, it is necessary to determine the optimum power of electromagnetic radiation, the duration of the heating and cooling stages and the number of treatment cycles in the field of ultrahigh-frequency currents.

At the first stage of the research, it was necessary to determine the temperature of

Table 1. Preliminary thermal and electromagnetic treatment of epoxy compositions

Mode number	Preliminary thermal treatment mode	Electromagnetic treatment mode
1	100°C, 30 min	10 s (destruction)
2	80°C, 1 h	10 s + (2 min) + 15 s (destruction)
3	50°C, 1 h	10 s + (30 s) + 15 s (destruction)
4		10 s + (30 s) + 10 s + (2 min) + 15 s
5		10 s + (1 min) + 15 s + (1 min) + 15 s
6		10 s + (2 min) + 20 s + (2 min) + 20 s
7		15 s (destruction)

Note. The cooling time is indicated in parentheses. The composition of epoxy composite material: 150 mass parts of copper oxide powder; 16 mass parts of copper powder; 2 mass parts of discrete carbon fiber. Power of electromagnetic treatment is 120 Watts.

the initial heat treatment, which was intended to transformation of the viscous epoxy composition into a solid state. This is due to the technological need, since the viscous composition must be compressed in a metal mold for sealing because of a high degree of filling the system. Then, the solid epoxy composite is removed from the mold and subjected to the treatment in an electromagnetic field. The complexity of the process is that the treatment in the electromagnetic field can not be carried out immediately in the metal mold; so the first step was a preliminary heat treatment.

It has been experimentally established that the epoxy composite material with an optimum content of reinforcing fillers is destructed as a result of processing in an electromagnetic field during the first 10 s (Table 1, Mode 1). This is explained by too high temperature (100°C) of the preliminary heat treatment, which results in the formation of a nonequilibrium structure. The reduction of the temperature of the preliminary heat treatment to 80°C allowed for completion of the first stage of the processing in the field of ultrahigh frequency currents (Table 1, Mode 2). The exposure duration was increased to 1h in order to warm the walls of the metal mold. However, after cooling for 2 min and subsequent treatment for 15 s, the destruction occurred, indicating still high pretreatment temperature. Therefore, the pretreatment temperature was reduced to 50°C with a 1 h exposure (Table 1, Mode 3). However, the destruction of the composite occurred at the second stage of the processing in the field of ultrahigh frequency currents, indicating too high processing time of 15 s at this stage. This is explained by the intense release of thermal energy, which does not dissipate within 30 s of cooling.

In the next mode (Table 1, Mode 4), the duration of the electromagnetic treatment was reduced to 10 s. This allowed the electromagnetic processing for 15 s without destruction of the structure. It became interesting, whether the increase in cooling time and the electromagnetic treatment time are connected.

The results of the next processing mode (Table 1, Mode 5) have shown experimentally a symbatic relationship between the cooling and heating processes in the epoxy-composite system.

An increase in the cooling duration allows for reducing the excess of thermal energy which causes the destruction of the polymer structure after the electromagnetic treatment. Therefore, the optimal cooling time depends, firstly, on the duration of the pre-treatment, and secondly, determines the duration of the subsequent treatment in the electromagnetic field. It has been experimentally established that if the first electromagnetic processing is carried out for 10 s, then the second processing duration should be also 10 s with sufficient cooling time of 30 s between the stages. However, if the second processing duration is increased to 15 s or 20 s (Table 1, Mode 6), then the pre-cooling duration should be increased to 1 min or 2 min, respectively.

It has been experimentally determined that the optimal duration of the electromagnetic treatment of the epoxy compositions is 10 s. As the processing duration increases to 15 s (Table 1, Mode 7), a large amount of thermal energy is accumulated in the material; this leads to an intense destruction of the epoxy composite. The electromagnetic treatment during less than 10 s is not feasible, because the thermal energy in the bulk of

Table 2. Electromagnetic treatment of the composition (power 120 W)

Sample number	Composition	Electromagnetic treatment mode
1	150 mass parts of copper oxide powder; 16 mass parts of copper powder; 2 mass parts of discrete carbon fiber	1) 10 s + (1 min) + 20 s (destruction)
		2) 10 s + (1 min) + 10 s + (2 min) + 15 s + (3 min) + 20 s (destruction)
		3) 10 s + (2 min) + 10 s + (2 min) + 15 s + (3 min) + 20 s
2	150 mass parts of copper oxide powder; 8 mass parts of carbon powder; 2 mass parts of discrete carbon fiber	4) 10 s + (1 min) + 15 s (destruction)
		5) 10 s + (1 min) + 10 s + (2 min) + 15 s (destruction)
		6) 10 s + (2 min) + 10 s + (2 min) + 15 s + (3 min) + 20 s

Note. The cooling time is indicated in parentheses.

the material is insufficient for structuring processes.

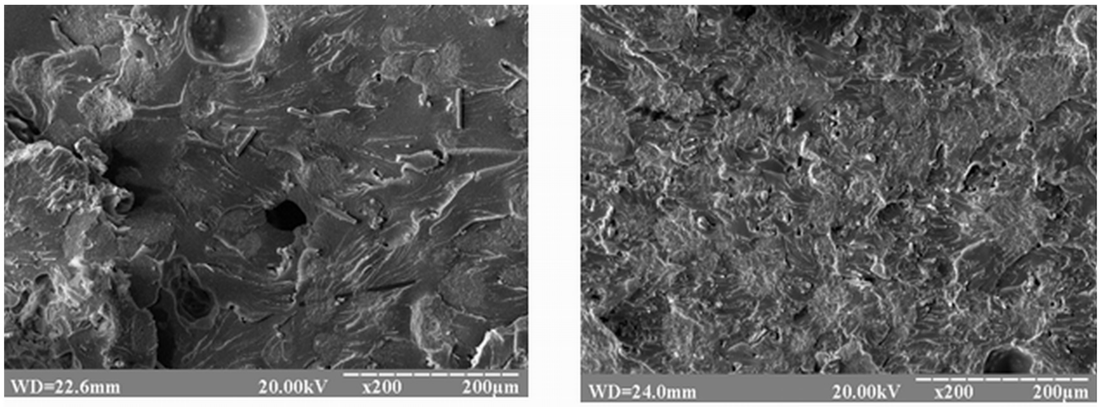
It was established that a slight increase of the electromagnetic treatment duration to 20 s in the second stage after cooling for 1 min (Table 2, Mode 1) resuts in the appearance of destruction of the polymer matrix due to lack of the pre-cooling. Reducing the second stage duration to 10 s after 1 min cooling (Table 2, Mode 2) allowed for three cycles of the treatment; but at the final stage, the epoxy composite was destructed. Therefore, it was assumed that a sufficient cooling (for 2 min) is important after the first stage of the cyclic treatment in the electromagnetic field (Table 2, Mode 3). This contributes to the uniform distribution of thermal energy over the volume of the material and initiates the processes of simultaneous formation of chemical bonds in all local volumes. At the second and third stages, the optimum duration of electromagnetic treatment is 10 s and 15 s, respectively, provided that the cooling duration is 2 min and 3 min, respectively, for the uniform structuring processes.

During the structuring of epoxy composites for tribotechnical purposes, the copper powder is introduced, which performs the function of solid lubricant. It is interesting to investigate the structuring processes of epoxy composites doped with the spherical graphite (nonmetal) powder, which performs a similar function. For the epoxy composit with the non-metallic filler, the second stage treatment duration was increased to 15 s (Table 2, Mode 4). (Note, that the metal particles do not transmit the electromagnetic radiation, thus, the formation of chemical bonds may be uneven, especially in the boundary areas near the surface of metal particles). This treatment duration was found to be too long; therefore the destruction of the epoxy composite occurred. This was explained by the insufficient cooling duration and overheating of the samples after the first stage of the electromagnetic treatment.

Reducing the processing duration to 10 s allowed for two cycles of the electromagnetic processing (Table 2, Mode 5); however, in the third stage, the destruction of the polymer matrix occurred, obviously, due to the unsufficient cooling of the material after the first stage of the electromagnetic processing.

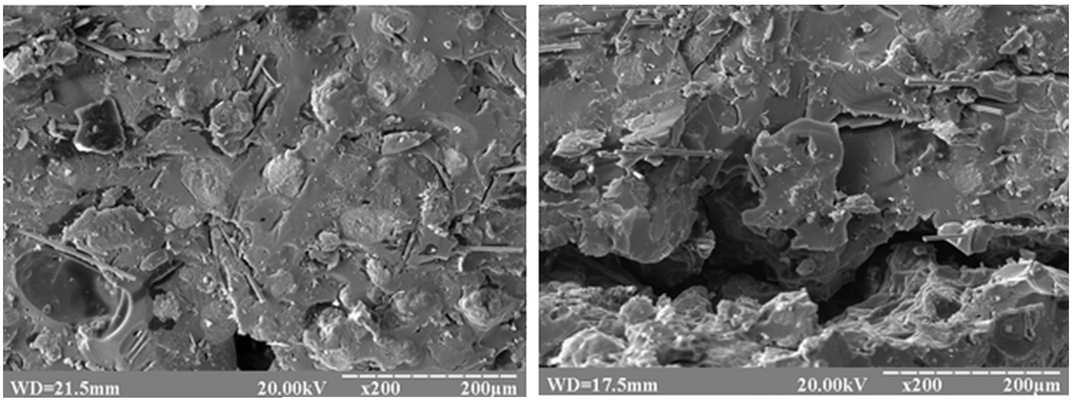
The increase of the cooling duration to 2 min (Table 2, Mode 6) allowed four cycles of electromagnetic treatment without any composite destruction. This indicates the ability of the epoxy composite to withstand the influence of electromagnetic radiation. It has been established that the epoxy composite material filled with the copper powder is more resistant to electromagnetic radiation. This is due to the higher thermal conductivity of the metal filler and the better ability to dissipate thermal energy in the bulk of the polymer matrix.

The surface of the fracture of the epoxy composite composition No. 1 with the copper filler (see Table 1) structured according to the classical heat treatment regime has a more developed relief (Fig. 1, a) compared to the fracture surface of the No. 2 sample (carbon powder) structured according to the similar classical mode of the thermal treatment. For the epoxy composite No. 1, no stratifications were revealed between the epoxy polymer matrix and the filler surface; this indicates a high degree of interaction and a strong adhesion bond between the components of the system. This provides a higher resistance of the epoxy composite filled with the copper powder to dynamic loads. The fracture surface of the No. 2 epoxy composite is rather flat (Fig. 1, b), which indicates a high fragility of the epoxy composite filled with the spherical graphite powder.



a) b)

Fig. 1. Factographs of the fracture of epoxy composites of composition No. 1 (a) and No. 2 (b) (Table 2), structured according to the classical mode of heat treatment.



a) b)

Fig. 2. Fractographs of the fracture of the epoxy composites of composition No. 1 (a) and No. 2 (b) after treatment in the electromagnetic field (b) (Table 2, Mode 5).

The Mode 2 electromagnetic treatment of the No. 1 epoxy composite (Table 2) results in partial loss of interaction between the epoxy polymer matrix and the fillers, which is manifested in stratifications on the surface of the fracture (Fig. 2, a). It is seen that the surface of the fracture is rather flat, and the particles of the filler are clearly identified on the surface of the fracture. This indicates that during a fragile fracture the crack was moving in one plane without obstacles. In the composite material, the energy dissipation occurs at the inclusions of another phase, provided that there is a strong bond between the matrix and the particles of the filler. Therefore, it can be argued that in this case, the unsufficient cooling duration after the first stage of the electromagnetic treatment results in the destruction of the structure in the boundary layers.

The Mode 5 electromagnetic treatment of the epoxy composition No. 2 resulted in the pronounced destruction of the sample; its structure was characterized by high porosity, bundles, and the presence of cavities (Fig. 2, b). These defects are formed due to the presence of spherical graphite particles with low adhesion and cohesive strength in the epoxy polymer matrix.

In the case of the electromagnetic field with a power of 240 W, the exposure duration was shortened to 5 s (Table 3, Mode 1), however, the epoxy composites were destructed; thus, the exposure duration was yet too long. Then the first stage processing duration was shortened to 3 s, and the sample was not destructed. So after 1 minute cooling, the Mode 2 processing was used for this sample (Table 3). However, after the third stage during 5 s, the epoxy composite specimens were destructed; this apparently was associated with a low exposure at the second cooling stage.

A positive result was obtained in the case of a step-by-step increase in the cooling time to 4 min (Table 3, Modes 3 and 4), but on the

Table 3. Electromagnetic treatment of compositions (power 240 W)

Mode number	Electromagnetic treatment mode
1	5 s (destruction)
2	3 s + (1 min) + 3 s + (1 min) + 5 s (destruction)
3	3 s + (1 min) + 3 s + (2 min) + 5 s (destruction)
4	3 s + (1 min) + 3 s + (3 min) + 5 s (destruction)
5	3 s + (1 min) + 3 s + (4 min) + 5 s + (5 min) + 5 s (destruction)
6	3 s + (1 min) + 3 s + (4 min) + 5 s + (6 min) + 5 s + (5 min) + 10 s + (3 min) + 5 s

Note. The cooling duration is indicated in parentheses.

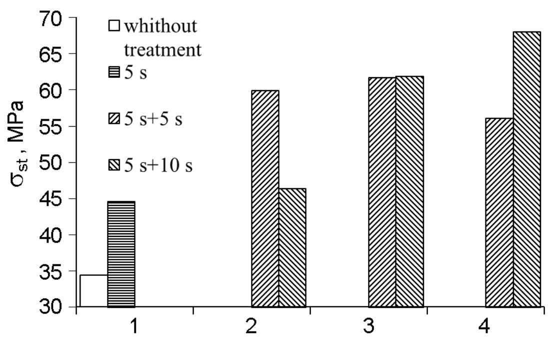


Fig. 3. Influence of electromagnetic treatment with a duration of 5 s on the first cycle on the strength of compression of epoxy composites with cooling.

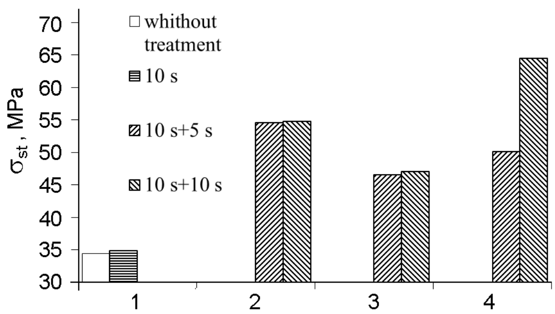


Fig. 4. Influence of electromagnetic treatment with a duration of 10 s on the first cycle on the strength of compression of epoxy composites with cooling between cycles: 2 - 1 min; 3 - 2 min; 4 - 3 min.

fourth processing cycle (Table 3, Mode 5), a destruction occurred. It was decided to increase the cooling duration to 6 min in the third stage (Table 3, Mode 6); this allowed for structuring the epoxy composites in six cycles. Moreover, after the third treatment cycle and the maximum cooling duration of 6 min, the structure was found to be stabilized; therefore the durations of fourth and fifth cooling stages were reduced to 5 min and 3 min, respectively.

Ultimate compressive strengths were measured in the samples with No. 1 composition (Table 2) that were preliminary thermally treated (50°C for 1 h). After the electromagnetic treatment, the classical stepwise heat treatment was carried out: 1 h — 50°C, 1 hour — 100°C, 4 h — 140°C, because the epoxy composites without the thermal treatment are plastically deformed without destruction.

It has been experimentally established that the epoxy composites not subjected to the electromagnetic treatment had the lowest compressive strengths of 34.1–34.6 MPa (Figs. 3, 4). Only one stage of the electromagnetic treatment for 5 s provided the increase of the compressive strength by 30 % (Fig. 3). The similar treatment for 10 s (Fig. 4) almost did not change the value of the compression strength, indicating the expediency of the electromagnetic treatment for 5 seconds. Apparently, the treatment during 10 s results in the destruction of bonds between the components of the system, causing stratification and acts as a source of cracks.

It has been experimentally established that after the electromagnetic treatment during 5 s at the first and second stages, the contact strength of the epoxy composites increases to 60–62 MPa in the case of applying the cooling to 2 min. After cooling for 3 min, a slight decrease in the strength (to 56 MPa) is observed; this is associated with a significant loss of thermal energy and the treatment duration (5 s) insufficient to provide the formation of additional chemical nodes. The treatment during 10 s in the second stage resulted in a gradual increase in the strength by 25–32 %, when the cooling durations were 2 min and 3 min. This indicates the importance of maintaining the optimum amount of thermal energy necessary for the formation of chemical bonds between the active groups of components of the epoxy composite material.

The two-stage treatment during 10 s in the first stage and 5 s in the second stage results in a decrease of 8–25 % of the compression strength, regardless of the exposure duration. This indicates that the 10 s duration of the first stage of the treatment provides thermal energy, which causes intense structure formation. The second stage for 5 s is not sufficient to prolong the structuring process of the epoxy composites. Increasing the second stage exposure to 10 s increases the compression strength in the case of cooling for 3 min due to an optimal amount of thermal energy in the first stage and a sufficient amount of new thermal energy in the second stage of the treatment.

For the tribotechnical studies, epoxy composite samples (composition No. 1, Table 2) have been formed. These samples were subjected to a preliminary heat treatment (50°C for 1 h). As a result of the analysis of the previous modes of the electromagnetic treatment, an optimal structuring regime of epoxy composites was developed, which consisted of the following cycles: 5 s (3 min) + 10 s (3 min) + 15 s (4 min) + 20 s (5 min) + 25 s (4 min) + 30 s.

The epoxy composites structured according to this mode have the lowest weight wear rate (0.064 mg/km) at a sliding speed of 0.35 m/s and a specific load of 0.4 MPa. As the sliding speed is reduced to 0.25 m/s, the weight wear rate increases by 50–60 %. With an increase in the sliding speed up to 0.45 m/s, the weight wear rate increases sharply by a factor of 2.4 to 3.3, respectively, 0.24 mg/km for the specific load of 0.42 MPa, and 0.156 mg/km for the specific load of 0.6 MPa. This is related to the formation of protective copper films on the contacting surfaces in the presence of copper powders added into the epoxy composites, and under favorable conditions for the friction interaction [8].

4. Conclusions

The preliminary heat treatment is necessary for partial structuring of high-filled epoxy composites in a metal mold. It is technically impossible to enter the metal mold into the electromagnetic field. The optimum heating mode is the holding of the sample at a temperature of 50°C for 20–60 min depending on the thickness of the walls of the metal mold.

The optimal duration of the first stage of the electromagnetic treatment is 5 s; the treatment for 10 s or more results in disruption of chemical bonds and stratification of the components of the epoxy composite. The optimum amount of thermal energy is necessary for the formation of chemical bonds between the active groups of components of the epoxy composite material.

Increasing the cooling duration allows for dissipation of the excessive heat energy, which causes the disruption of the bonds between the components of the epoxy composites. However, prolonged cooling increases the duration of the tecnological process and requires additional heat energy to restore the structuring process.

It was established that the duration of the next stage of the electromagnetic treatment is directly proportional to the duration of cooling in the previous stage. In the second stage, the optimal treatment duration is 10 seconds; this allows the composite to get a new portion of thermal energy.

It has been established that the tribotechnical epoxy composite material, additionally filled with copper powder, is more resistant to electromagnetic radiation; this is associated with higher thermal conductivity of the metal filler in comparison with graphite powder and the ability to dissipate thermal energy better.

The number of electromagnetic treatment cycles for epoxy composites is determined by the final cooling stage, which duration is reduced in comparison with the previous stage. In order to complete the structuring processes, and to achieve high physical-mechanical and operational characteristics, the electromagnetic treatment should consist of 6–10 cycles depending on the nature of the fillers that determine thermal energy dissipation.

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