Lecture Notes in Networks and Systems 1070

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New Technologies, Development and Application VII

Advanced Production Processes and Intelligent Sytems, Volume 2

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Contents

Carbon Plastics for Structural Purposes Based on Aromatic Polyamide Phenylone C-2

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Abstract. For the purpose of creating a plastic for structural purposes, the aromatic polyamide phenylone C-2 was reinforced with chromium-containing carbon fiber in an amount of 17 wt. %. As a result of a set of studies of the structure, thermophysical, physico-mechanical and tribological properties, it was found that the reinforcement of aromatic polyamide makes it possible to obtain a material with improved performance characteristics. The engineered carbon fiber having high thermal resistance, thermal conductivity and wear resistance is characterized by a low linear expansion thermal coefficient and friction factor, is operable in a wide range of specific pressures and sliding speeds and can be used for products operating in friction units of movable joints of machines and machinery.

Keywords: aromatic polyamide · chromium-containing carbon fiber · carbon plastics · properties

1 Introduction

One of the priority areas of scientific studies in the field of polymer materials engineering is the development of functional structural materials with high thermal shock resistance, improved physico-mechanical and tribological properties, intended to be used in specific areas.

Phenylone C-2 (TU 6-05-221-226-72) is a high-quality structural material capable of being used for operation under the effect of large static and dynamic loads in the temperature range from −80 °C to +200 °C. Phenylone C-2 is well processed; its distinctive feature is the combination of high rigidity and strength with high fracture toughness [1, 2]. In terms of strength parameters, phenylone C-2 surpasses most of the known unfilled plastics and is second only to glass plastics [3, 4].

Despite the high physical and mechanical properties, phenylone C-2 has good performance capability only under conditions of lubrication (oil, water), while in the dry friction mode it has high friction factor values and a narrow range of the RV criterion, which significantly limits its operational capabilities.

One of the effective methods of improving the tribotechnical characteristics of polymers is the reinforcement of the polymeric matrix with carbon fibers (CF).

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2 Computational Details

The carbon-fiber-based polymer composites – carbon plastics (CP) [5, 10] are characterized by high values of resistance to fatigue loads, damping capacity and vibration resistance, electrical conductivity and chemical stability; low thermal coefficient of linear expansion, which ensures an insignificant change in the product size when heating and cooling them.

Due to the high performance characteristics the carbon plastics have found wide application in various industry fields, ranging from rocket and space and aviation equipment, automotive engineering, shipbuilding to sports equipment and household appliances [6–8].

For the purpose of creating a new carbon plastics for structural purposes the aromatic polyamide phenylone C-2 was reinforced with chromium-containing carbon fiber (Cr-CF) in an amount of 17 wt. %.

Chromium-containing carbon fiber that contains chromium oxide Cr_2O_3, at a heat treatment temperature of 800–900 °C it catalyzes the formation of a phase of nanoscale lattice-ordered carbon, the structural element whereof are graphene layers. The presence of nanoscale phases of metal and lattice-ordered carbon in the micron-scale Cr-CF structure (fiber diameter is about 6–8 microns) gives the fiber filler a set of new properties characteristic for nanoscale objects and opens up wide opportunities for their practical application, in particular, for the manufacture of parts for structural purposes [9, 11].

2.1 Results and Discussion

As previously conducted scientific studies have shown, the introduction of metal into the carbon fiber structure improves its wetting property with polymer binders and affects the interaction between the polymer and the filler at the interface of phases, which improves the carbon fiber strength properties [12].

At the initial stage, structural studies of the binder and carbon plastic based thereon were carried out. IR-spectral analysis of plastics was performed using the X-29 spectrophotometer. The preparation of study samples was performed by pressing the substance into a potassium bromide tablet: about 50 mg of the sample was ground into 600 mg of potassium bromide, then subjected to significant compression in a metal mold.

As a result of the study, it was found that the carbon plastic IR-spectrum in general outline reproduces the phenylone C-2 spectrum (Fig. 1). A wide band (almost from 4000 to 1800 cm^{-1}) with weakly pronounced maxima was observed in the area of stretching vibrations of hydrogen atoms. It is the result of overlapping bands of bound and free amide NH-groups, the maxima in the area of 3250 and 3050 cm^{-1} refer to stretch vibrations of hydrogen-bonded NH-groups. The intense absorption bands typical for aromatic polyamides and characteristic for phenylone C-2 were appeared in the area of 1700–1200 cm^{-1}.

These are the Amide I, Amide II and Amide III bands in the region of 1660, 1550 and 1245 cm^{-1} and narrow intense bands corresponding to the fluctuations of aromatic fragments (1605, 1530 and 1480 cm^{-1}). In the area of 1200–400 cm^{-1}, less intense absorption bands appeared, among which a note should be made of the deformation

bands of hydrogen atoms of aromatic fragments 860 cm^{-1} and a number of bands 780, 719 and 683 cm^{-1} related to vibrations of amide groups.

Despite the fact that the carbon plastic spectrum is generally similar to the phenylone C-2 spectrum, some differences are observed therein. In particular, in the spectrum of carbon plastic, the Amide III band is expanded in the high-frequency direction, which results in shifting of its maximum to 1248 cm^{-1}. The spectrum also contains extra bands near Amide I at 1640–1650 cm^{-1} (here in the phenylone C-2 spectrum only a relatively weak shoulder was observed). A note should be made of the notable expansion of the 781 cm^{-1} band and the strengthening and expansion of the 1080 cm^{-1} band. The latter leads to the fact that in the carbon plastic range it appears to be shoulder-like.

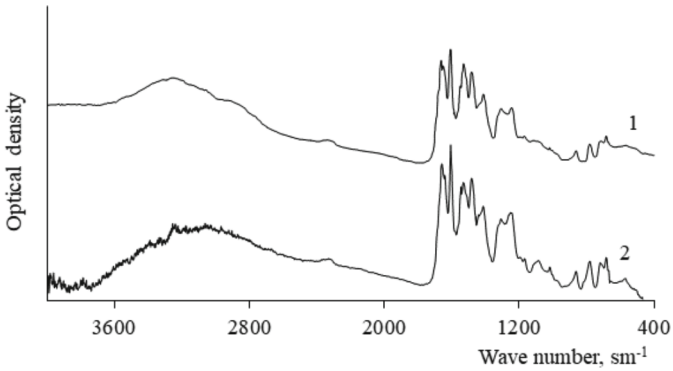


Fig. 1. IR absorption spectra of phenylone C-2 (1) and carbon plastic on it's basis, reinforced with 17 wt. % Cr-CF

Since all these features refer to changes in amide-fragment-related bands, it may be concluded that the fibrous filler affects the polyamide matrix structure, whereby this effect relates specifically to amide groups.

The X-ray diffraction analysis was carried out using the Dron-2.0 unit in copper radiation with a nickel filter. A set of experimentally obtained maxima on diffraction patterns was described by two characteristics: scatter angle 2θ and relative intensity.

The X-ray diffraction studies have made it clear that a wide intense peak in the area of the scatter angle $2\theta = 22.6$ rad, characteristic of phenylone C-2, was also appeared on the carbon plastic diffractogram as well (Fig. 2). On the carbon plastic diffraction pattern the amorphous ring on the curves in the area of Wulf-Breg angles $2\theta = 20$–30 rad significantly decreased, which was illustrative of a more crystalline carbon plastic structure as compared to the polymer binder.

One of the effective methods for predicting the behavior of polymer composites in high temperature conditions is thermal analysis allowing to note changes occurring when heating of the material with subsequent release or absorption of heat [12].

The data of the thermogravimetric analysis of Cr-CF were indicative of the high thermal resistance of the fiber: in the temperature range of 300–423 K, a gradual reduction in mass of the reinforcing filler (0.4–4.2%) was observed due to the moisture removal from the samples and only at a temperature of 1073 K the fiber began losing 9% of the

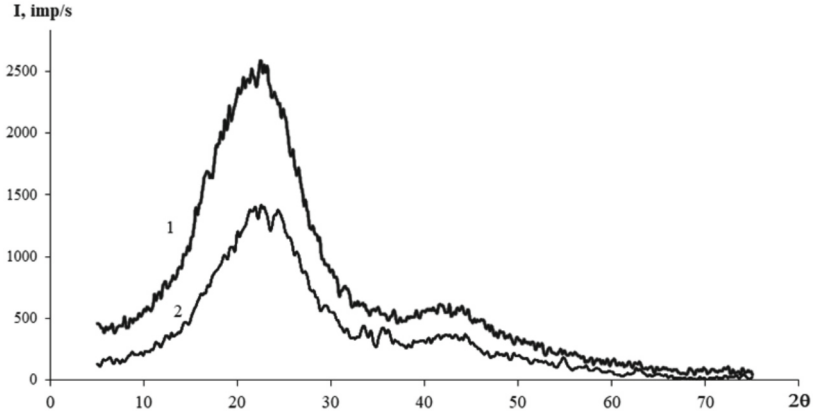


Fig. 2. Diffraction patterns of phenylone C-2 and carbon plastic based thereon, reinforced with 17 wt.% Cr-CF

mass. Therefore, it is quite predictable that the reinforcement of phenylone C-2 Cr-CF allowed increasing its thermal resistance (Fig. 3, Table 1). In particular, the temperature at which 10, 20 and 30% mass loss of carbon plastic samples was observed was 19, 22 and 35 °C higher, respectively, than for the initial polymer.

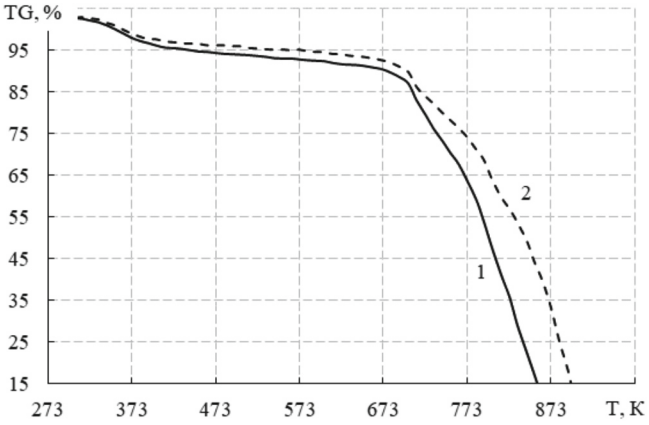


Fig. 3. Curves of thermogravimetric analysis of phenylone C-2 (1) and carbon plastic based thereon, reinforced with 17 wt. % Cr-CF (2)

The data of thermal studies showed that intensive destruction of materials, accompanied by a significant mass loss, began to appear at temperatures above 873K. On the curve of differential thermal analysis, an exothermic peak revealed in this area, characterizing the decomposition process of the polymer binder [2], whereby while its value for carbon plastic was greater as compared to phenylon C-2, which is indicative of a more intensive decomposition process of carbon plastic [13, 14].

Table 1. Thermal resistance of phenylone C-2 and carbon plastic based thereon

Material	Temperature, K		
	T_{10}	T_{20}	T_{30}
C-2	680	725	755
C-2 + 17 wt. % Cr-CF	699	747	790

T_{10}, T_{20}, T_{30} are the temperatures of 10, 20 and 30% mass loss, K.

Along with an increase in thermal resistance, the developed carbon plastic showed better improved thermophysical and physico-mechanical characteristics (Table 2). The specific heat capacity of carbon plastic in the temperature range of 173–498 K was on average 15% lower than that of phenylone C-2; the drop in the linear expansion thermal coefficient as a result of measurements in the temperature range of 298–558 K varied from 20 to 60%, and the thermal conductivity coefficient and strength parameters increased [13].

Table 2. Thermophysical and physico-mechanical parameters of phenylone C-2 and carbon plastic based thereon

Parameters	Phenylone C-2	Phenylone C-2 + 17 wt. % Cr-CF
Thermal conductivity coefficient λ, W/m ·K at a temperature of 323 K	0.27	0.52
Temperature linear expansion thermal coefficient, $\alpha \cdot 10^{-6}$, K^{-1} in the temperature range of 298–558 K	43.2	17.6
Ultimate compressive strength $\sigma_{compr.}$, MPa	361	368
Compression yield strength σ_{st}, MPa	202	221
Compression elasticity modulus E, MPa	3314	3438
Surface hardness after abrasive friction testing Ra, μm	5.8	3.6

The study of tribological properties of aromatic polyamide and carbon plastic based thereon in the dry friction mode was carried out on a disc friction machine. The sample wear was evaluated according to the disk scheme (steel 45, HRCэ 50, Ra = 0.08) – a carbon plastic sample (Ø 10 mm, height 10 mm) at specific loads P = 0.2–0.8 MPa, sliding speeds υ = 1, 1.5, 2.0 m/s, the friction path was 1000 m. The wear of samples was determined using the analytical scales VLR-200 with an accuracy of 0.0002 g.

The results of studies of operating modes affecting the tribological properties of samples indicated that with an increase in specific pressure and sliding speed, the carbon plastic coefficient of friction decreased (Fig. 4a).

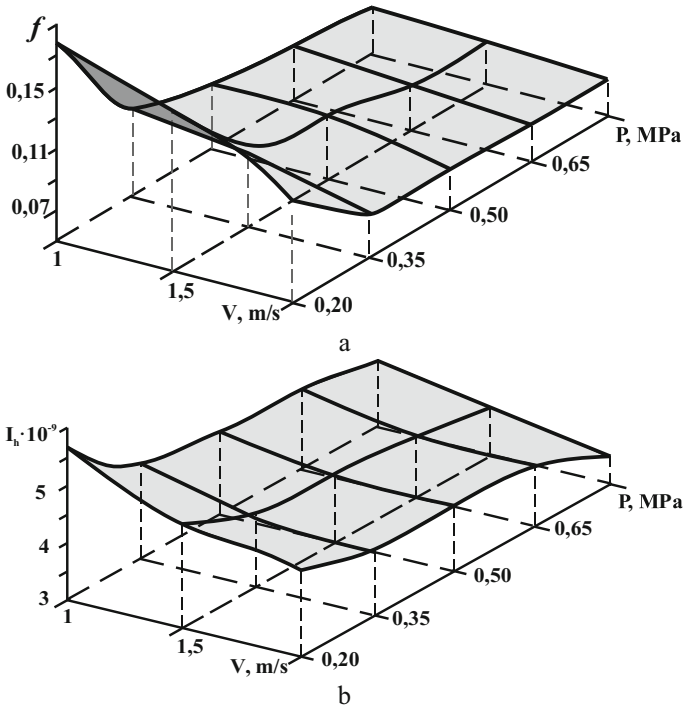


Fig. 4. Operating modes affecting the coefficient of friction (a) and the linear wear intensity (b) of carbon plastic based on phenylone C-2

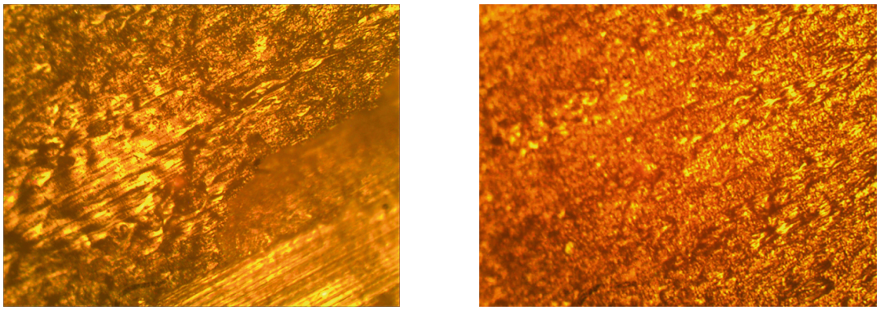
In particular, in the course of operation of carbon plastic samples under sliding speeds of 1, 1.5 and 2 m/s with an increase in the specific load from 0.2 to 0.8 MPa, the carbon plastic coefficient of friction decreased by 42–56%, correspondingly. At the minimum specific pressure ($P = 0.2$ MPa) with an increase in the sliding speed from 1 to 2 m/s, the coefficient of friction decreased from 0.16 to 0.12, and at the maximum ($P = 0.8$ MPa) it was in the range of 0.08–0.07.

Along with a decrease in the coefficient of friction, the toughening of operating modes led to an increase in the carbon plastic wear resistance. With an increase in the specific pressure and sliding speed, the intensity of linear wear of carbon plastic decreased by more than 20%.

The coefficient of friction of phenylone C-2 under the study loads and sliding speeds varied from 0.13 to 0.18 and showed higher values as compared to carbon plastic, and the linear wear intensity with tightening of operating modes increased for the polymer from $6.5 \cdot 10^{-9}$ up to $1.5 \cdot 10^{-8}$.

In the event of friction of phenylone C-2 with low values of the thermal conductivity coefficient (Table. 2) localization and accumulation of heat occurs in the friction zone, which leads to an increase in the segmental mobility of macromolecules, an increase in adhesion, resulting in an increase in the coefficient of friction and damage to the friction surface of the polymer (Fig. 5a). The presence of strong adhesive bonding leads to the

destruction of the protective surface film formed on the counterbody in the course of the polymer wearing-in, the process of setting-up the polymer with the counterbody material begins to progress, therefore its friction factor and the linear wear intensity have high values.



a b

Fig. 5. The appearance of a sample of phenylone C-2 (a) and of carbon plastic based thereon (b) after studies in the dry friction mode under specific load of $P = 0.8$ MPa and sliding speed of $\upsilon = 2$ m/s

The performance capability criterion PV (the product of the specific pressure by the sliding speed) for phenylone C-2 was no more than 1.2 MPa · m/s. It probably has to do with the development of a high temperature on the steel counterbody surface, which caused the friction surface of the polymer sample to soften and for the material to lose its operability (Fig. 5a). The carbon plastic sample showed steady performance up to the maximum values of the operating modes, whereby the friction surface remained unchanged (Fig. 5b), the criterion for carbon plastic was 1.6 MPa ·m/s.

The reinforcement of phenylone C-2 with chromium-containing CF almost doubled its thermal conductivity (Table 2); this contributes to better heat dissipation from the friction zone of the carbon plastic sample, which positively affects the change in its tribological properties.

As compared to the original polymer, the engineered carbon plastic showed a coefficient of friction lower more than by 2 times and a linear wear intensity by 2–35 times, which allows it to be used as an material of anti-frictional purpose for friction units of movable joints.

3 Conclusion

In general, the conducted set of studies testifies that the reinforcement of aromatic polyamide phenylone C-2 allows to significantly improve its performance characteristics. The developed carbon plastic shows improved thermal, thermophysical and physico-mechanical properties.

The study of the main regularities of the process of friction and wear of materials has shown that carbon plastic based on phenylone C-2 has anti-friction properties and

high wear resistance, which allows it to be recommended to be used as a material for the structural purpose of friction units of machines and machinery in order to increase the service life of products based thereon.

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