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POLYMER COMPOSITE MATERIALS OF SPECIAL PURPOSE FOR THE AEROSPACE AND ROCKET INDUSTRY

Introduction. *The advancement of the aviation and space industry has not only led to the creation of modern aircraft, rockets, and spacecraft but has also positively influenced related industries.*

Problem Statement. *A critical requirement for aviation and space industry products is a high level of reliability and durability due to their continuous interaction with humans and the significant costs of production and operation. This is particularly relevant for modern aircraft, rockets, and spacecraft, which operate at higher speeds, temperatures, and loads than their predecessors. Therefore, enhancing the reliability and durability of such products has become a pressing challenge.*

Purpose. *The purpose of this research is to increase the reliability and durability of key components in rocket and space technology by replacing conventional materials with newly developed ones.*

Materials and Methods. *The research has focused on polymer composite materials (PCMs) based on fluoropolymers and aromatic polyamides, filled with dispersed materials derived from silicon dioxide and carbon.*

Results. *Formulations and processing technologies for PCMs based on fluoropolymers and aromatic polyamides have been developed. These materials have been shown to surpass most non-ferrous metals, their alloys, and low-carbon steels in strength (up to 285 MPa) while maintaining a low density (up to 1400 kg/m^3). In terms of thermophysical properties, they have demonstrated exceptional heat resistance, with no thermal decomposition observed up to +365 °C. Furthermore, parts manufactured from these materials have proven capable of operating in friction nodes without lubrication under normal loads of up to 2.5 MPa.*

Conclusions. *The developed polymer composite materials based on fluoropolymers and aromatic polyamides exhibit a high level of mechanical and thermal properties. Components made from these materials significantly enhance the reliability and durability of modern aircraft, rockets, and spacecraft, representing a substantial advancement for the aerospace and rocket industry.*

Keywords: polymer composite materials, fluoropolymers, aromatic polyamides, physical and mechanical properties, friction, wear, aviation and space industry.

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Progress in the development of humanity is practically impossible without high-tech industries, which serve as its primary driving force. Among the most high-tech production sectors are the aerospace and rocket industries. These industries currently evolve along two main directions: structural modernization and the integration of advanced materials into the key components of their equipment [1, 2].

The first direction demonstrates high efficiency in the long term but involves significant financial and human resources. The second direction proves more effective in the short and medium term and requires fewer resources, making it more relevant. This assertion aligns with the principles of the European Commission's Key Enabling Technologies (KETs), which highlight the development of new materials as one of the main priorities.

It is known [3] that the key components of machines and mechanisms in the aerospace and rocket industries operate under harsh conditions (high levels of stress, temperatures, speeds, etc.). These components are expected to ensure sufficient reliability and durability of aircraft and rockets, often determined by the materials from which they are made. Thus, the materials used for the main parts and assemblies of machines and mechanisms in these industries must exhibit high levels of physical-mechanical, thermophysical, and tribological properties [4].

Most parts of modern aircraft and rockets are produced from a wide range of materials, including metals and their alloys, polymers and polymer-based composite materials, ceramics, and glass. Among these, polymers and polymer composite materials (PCMs) stand out as the most promising [5, 6]. For example, it is noted [7] that leading global aerospace companies, Airbus Group and Boeing Company, manufacture over 50% of their aircraft components from these materials, and their share continues to grow annually. Additionally, according to the BBC Research Report Overview, *Engineering Resins, Polymer Alloys, and Blends: Global Markets* (April 2022), the global market for structural polymers and their composites is projected to grow from USD 70.7 billion in 2021 to USD 94.0 billion by 2026. This data indicates that polymers and PCMs are among the most promising materials for manufacturing machine components and mechanisms in the aerospace and rocket industries.

The demand for components made of polymers and polymer composite materials (PCMs) in the aerospace and rocket industries is driven by their unique set of properties. These materials feature a low density (0.8—2.5 g/cm^3) while providing sufficient strength (150—250 MPa), which is particularly relevant for aircraft and rocket construction. Their application enables not only a substantial reduction in the weight of aircraft and rockets but also allows their use in medium- and high-load assemblies [8—10]. Polymers also exhibit a high level of resistance to aggressive environments (acids, alkalis, bases, etc.) and can function under alternating loads in structural assemblies. One of their key advantages is the ability to operate in friction units with minimal or boundary lubrication [11]. Additionally, polymers are relatively inexpensive materials with straightforward processing technologies for manufacturing components [12, 13].

Given these advantages, it is clear that integrating polymer-based components into the assemblies of aircraft and rockets can significantly reduce costs, enhance operational performance, and improve reliability and durability.

In modern aviation and space technology, materials such as fiberglass, organoplastics, and carbon plastics are widely employed. These materials combine low densities (1.4—1.6 g/cm^3) with high mechanical properties, such as yield stress and compressive modulus reaching up to 500 MPa and 7 GPa, respectively. This combination of properties makes plastics and composites based on them suitable for high-load assemblies in aerospace vehicles. However, these materials have notable drawbacks. They are associated with high production costs due to the use of expensive components and complex manufacturing technologies. Furthermore, most polymers and polymer composites currently used in aerospace and rocket engineering exhibit insufficient tribological properties, which limits their application in friction units of aerospace vehicles.

The creation of polymer composite materials (PCMs) that combine high physical-mechanical properties, low production costs, and the ability to function in aircraft and rockets not only as structural materials but also as tribological materials is of significant interest.

To develop PCMs that exhibit superior physical-mechanical and tribological characteristics while maintaining affordability, the following approaches are employed:

- **Selection of high-strength and heat-resistant polymer matrices and fillers** that provide a foundation for robust material properties.
- **Choosing polymer matrices and fillers capable of interacting during processing**, resulting in materials with enhanced properties.
- **Modernizing existing technologies or developing new methods for PCM processing**, enabling the improvement of material performance.

Each of these approaches has specific strengths and limitations. While they enable the production of PCMs with high-performance properties to varying degrees, the most optimal and effective approach for creating such materials has not yet been identified. Consequently, the task of developing a new and highly efficient approach remains pressing.

This work proposes a combined approach to the creation of high-performance PCMs, integrating the best elements from all the previously mentioned strategies. This approach involves developing PCMs based on strong and heat-resistant polymer matrices and fillers that exhibit high compatibility and interaction, while employing a novel, resource-efficient processing technology to produce these materials.

Among the polymers with high-performance properties, fluoropolymers, aromatic polyamides and polyimides, polyester- and polyarylether ketones, and phenolic resins are noteworthy [14—17].

From these, fluoropolymers (due to their excellent thermal stability and tribological properties) and aromatic polyamides (for their high strength and thermal resistance) were selected.

As fillers, fine-dispersed materials based on carbon and silicon dioxide were chosen [18—21]. These materials were selected because of their low cost (stemming from their abundant availability on Earth) and their ability to physically and chemically interact with the chosen polymer matrices. This interaction is facilitated by their well-developed surface area (up to 300 m^2/g) and, in the case of silicon dioxide, the presence of active silanol groups on its surface.

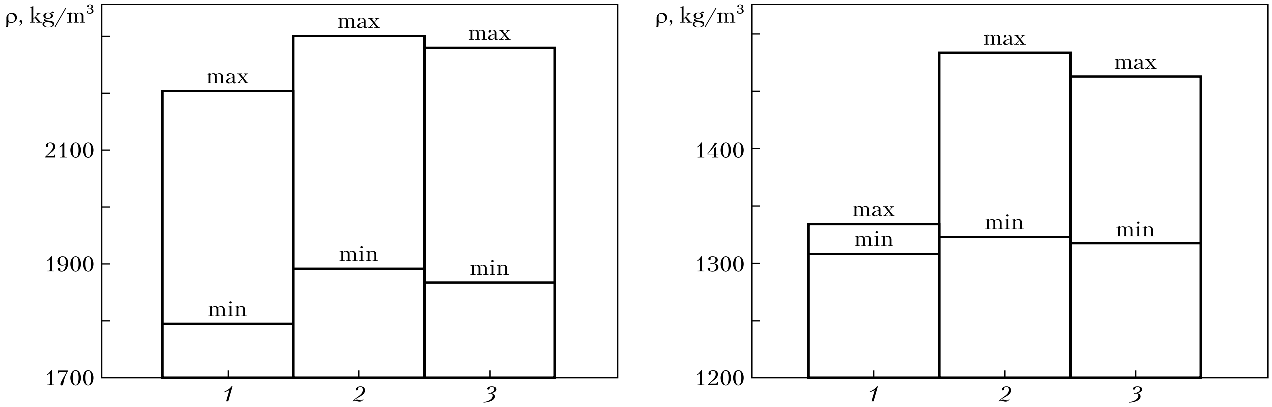
Based on preliminary studies [22, 23], the filler content in the polymer matrices ranged from 5% to 40% by weight.

The developed PCMs were produced both by the standard method (mechanically combining the initial components of the compositions) and through a novel resource-efficient technology. This innovative approach involves in-situ combination of the initial components of the polymer compositions [24—26].

One of the primary characteristics of materials for machine parts and mechanisms is their physical-mechanical properties. These properties affect the overall weight of parts, their strength, deformation characteristics, and more. Therefore, the development of materials with high physical-mechanical properties is a critical task.

The results of research on the physical-mechanical properties of the developed PCMs based on fluoropolymers and aromatic polyamides are shown in Fig. 1.

According to the results of density studies (Figure 1, *a, b*), the density of the developed polymer composite materials (PCMs) ranges from 1900 to 2200 kg/m^3 for fluoropolymer-based PCMs and from 1900 to 2200 kg/m^3 for aromatic polyamide-based materials. These values are 2.5 to 5 times lower than those of steels and non-ferrous metals. Based on this, it can be asserted that the use of components made from the developed PCMs instead of their metal counterparts, which operate under loads up to 280 MPa without experiencing significant deformations, would significantly

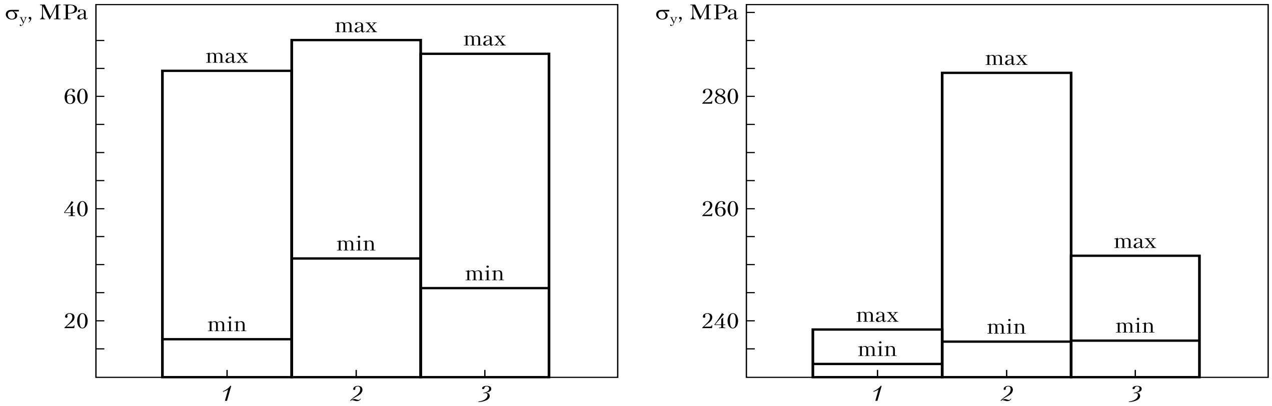


1 — Original fluoropolymers; *2* — fluoropolymers filled with silicon dioxides; *3* — fluoropolymers filled with carbon materials

a

1 — Original aromatic polyamides; *2* — aromatic polyamides filled with silicon dioxides; *3* — aromatic polyamides filled with carbon materials

b

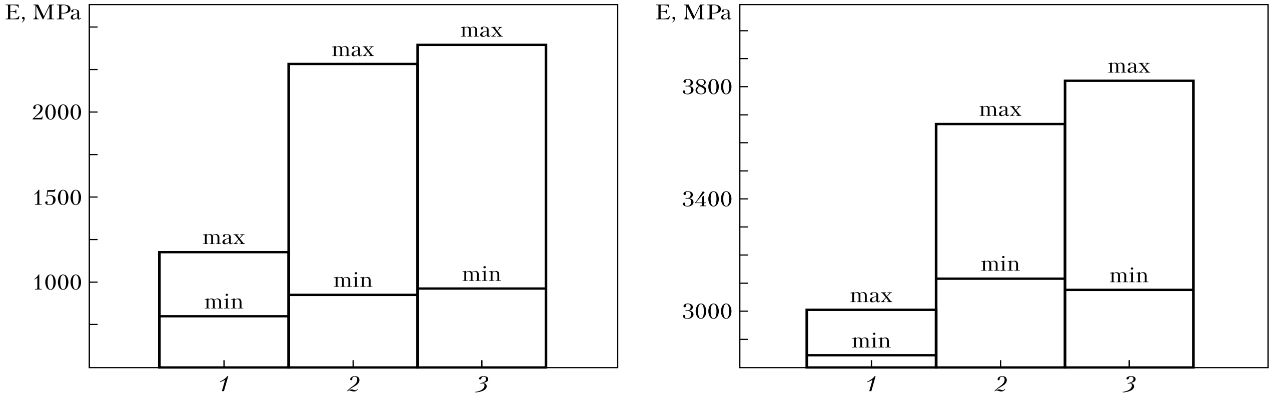


1 — Original fluoropolymers; *2* — fluoropolymers filled with silicon dioxides; *3* — fluoropolymers filled with carbon materials

c

1 — Original aromatic polyamides; *2* — aromatic polyamides filled with silicon dioxides; *3* — aromatic polyamides filled with carbon materials

d



1 — Original fluoropolymers;
2 — fluoropolymers filled with silicon dioxides;
3 — fluoropolymers filled with carbon materials

e

1 — Original aromatic polyamides; *2* — aromatic polyamides filled with silicon dioxides; *3* — aromatic polyamides filled with carbon materials

f

Fig. 1. Density (*a, b*), yield stress (*c, d*), and modulus of elasticity (*e, f*) under compression for materials based on fluoropolymers (*a, c, e*) and aromatic polyamides (*b, d, f*)

reduce the weight of aircraft. This reduction would, in turn, enhance the payload capacity of the aircraft.

The results of studies on the yield stress (Figure 1, *c, d*) and the modulus of elasticity under compression (Figure 1, *e, f*) of the developed PCMs based on fluoropolymers and aromatic polyamides indicate that these materials exhibit a fairly high level of mechanical properties, both compared to polymeric and metallic materials. Notably, the aromatic polyamide-based PCMs demonstrate exceptional performance, with a yield stress under compression reaching 285 MPa. This value exceeds that of most non-ferrous metals and approaches that of carbon steels. Additionally, the developed PCMs display a modulus of elasticity as high as 3900 MPa, surpassing the performance of most polymer-based materials.

Based on the conducted physical and mechanical studies, it can be concluded that the developed PCMs based on fluoropolymers and aromatic polyamides outperform most known polymer- and metal-based materials. They can be recommended as structural materials for the production of aircraft components, enabling significant weight reduction while maintaining a high level of strength properties.

It is known [27, 28] that most polymers exhibit low values of thermal and heat resistance, which limits their widespread use across various industries. Therefore, studies on the thermophysical properties of the developed polymer composite materials (PCMs) based on fluoropolymers and aromatic polyamides were conducted. The results are presented in the table below.

The thermal resistance of the developed PCMs, defined as the temperature at which the chemical bonds in the polymer matrix begin to degrade under heat, is determined by the onset temperature of active thermal decomposition. According to the obtained results, this temperature reaches 360 °C, which significantly exceeds the corresponding parameter for most known polymer-based materials. Based on this, the developed materials can operate in machine and mechanism components without thermal destruction at temperatures up to 360 °C.

The operational temperature limit of components under load without significant changes in geometric dimensions is determined by the Vicat softening temperature. For the developed PCMs based on fluoropolymers and aromatic polyamides, these values reach 290—300 °C. This confirms the feasibility of using components made from the developed PCMs in machine and mechanism parts at these temperatures, significantly surpassing the performance of most known polymer materials.

Notably, the developed PCMs exhibit relatively low values of linear thermal expansion. The minimum value is observed in PCMs based on aromatic polyamides, measuring 300×10^{-7} 1/°C, which is considerably better than that of most polymers [29]. This characteristic is particularly critical for tribological components of machines and mecha-

Table. **Thermophysical Properties of the Developed PCMs Based on Fluoropolymers and Aromatic Polyamides**

No.	Property	Materials					
		Fluoropolymers			Aromatic polyamides		
		Original	With silicon dioxides	With carbon materials	Original	With silicon dioxides	With carbon materials
1	Temperature of onset of active decomposition, °C	335—350	340—350	340—345	350—355	360—365	350—355
2	Vicat softening temperature T_{VC}, °C	160—180	220—280	190—210	275—290	295—305	292—295
3	Linear thermal expansion coefficient α, $\times 10^{-7}$ 1/°C	850—950	370—420	410—500	380—400	300—320	340—350
4	Shrinkage, %	—	—	—	0.95	0.4—0.6	0.7—0.9

nisms, which often consist of two dissimilar materials. Under thermal expansion, excessive changes in size can lead to the jamming of tribological assemblies, a risk minimized by the low thermal expansion of the developed PCMs.

According to the conducted studies of the thermophysical properties of the developed PCMs based on fluoropolymers and aromatic polyamides, it can be asserted that they are among the most thermally resistant polymer-based materials. Components made from these PCMs can operate in machine and mechanism assemblies, including tribological units, while maintaining their properties at a high level under loads and temperatures up to 300 °C. Additionally, it is noteworthy that the developed PCMs can withstand temperatures up to 360 °C without undergoing thermal decomposition. This opens possibilities for their application at these temperatures as coatings or materials for components that are not subject to significant loads.

One of the critical assemblies influencing the reliability and durability of mechanisms as a whole is the tribological unit. The quality of these units is predominantly affected by the materials used to manufacture the interacting friction components. Polymer-based materials, in particular, stand out because they can operate in tribological assemblies without lubrication. This significantly simplifies the design by eliminating oil stations and reduces the cost of machines, mechanisms, and the products they produce.

Previous studies [30—35] identified the optimal filler content in the developed PCMs in terms of their tribological properties. They also demonstrated that composites filled with carbon-based materials exhibit the lowest friction coefficients and the highest wear resistance. Of interest is determining the maximum load values under which components made from the developed PCMs can operate normally while maintaining a high level of reliability and durability. Figure 2 presents the results of tribological studies on the developed PCMs based on aromatic polyamide and fluoropolymer filled with carbon materials.

According to the conducted research, the developed materials exhibit some of the best tribological performance indicators compared to leading counterparts [36, 37]. Notably, materials based on fluoropolymers demonstrate lower friction coefficients and superior wear resistance. The observed dependencies of the friction coefficient and linear wear intensity of the developed PCMs on load during frictional interaction with steel show similar trends. For aromatic polyamide-based materials, the friction coefficient decreases within the range of 0.5 to 1.5 MPa, followed by stabilization and a sharp increase beyond 3 MPa. In contrast, fluoropolymer-based materials exhibit a friction coefficient reduction from 0.5 to 2.5 MPa, with a subsequent sharp increase starting around 3.5 MPa. The reduction in the friction coefficient with increasing load is characteristic of antifriction materials [38], attributed to specific calculation features. The subsequent increase in this parameter correlates with intensive frictional heating of contact surfaces, potentially leading to seizure in the tribological unit at high values.

The dependencies of linear wear intensity on load for the tested materials indicate an increase in wear with rising load. For aromatic polyamide-based materials, the wear intensity increases steadily within the range of 0.5 to 2.0 MPa. For fluoropolymer composites, this steady increase extends up to 2.5 MPa, after which a sharp rise is observed. Steady wear growth with increasing load is indicative of normal operation of the tribological unit, while abrupt increases signal a transition to an emergency operating mode. A clear correlation is evident between the friction coefficients and linear wear intensities of the tested materials as the load on the tribological unit changes. Therefore, the maximum loads under which components made from the developed PCMs can operate in normal mode are determined to be 2.0 MPa for aromatic polyamide-based materials and 2.5 MPa for fluoropolymer-based materials. Beyond these loads, emergency wear of the tested materials occurs, accompanied by sharp increases in both the friction coefficient and wear intensity.

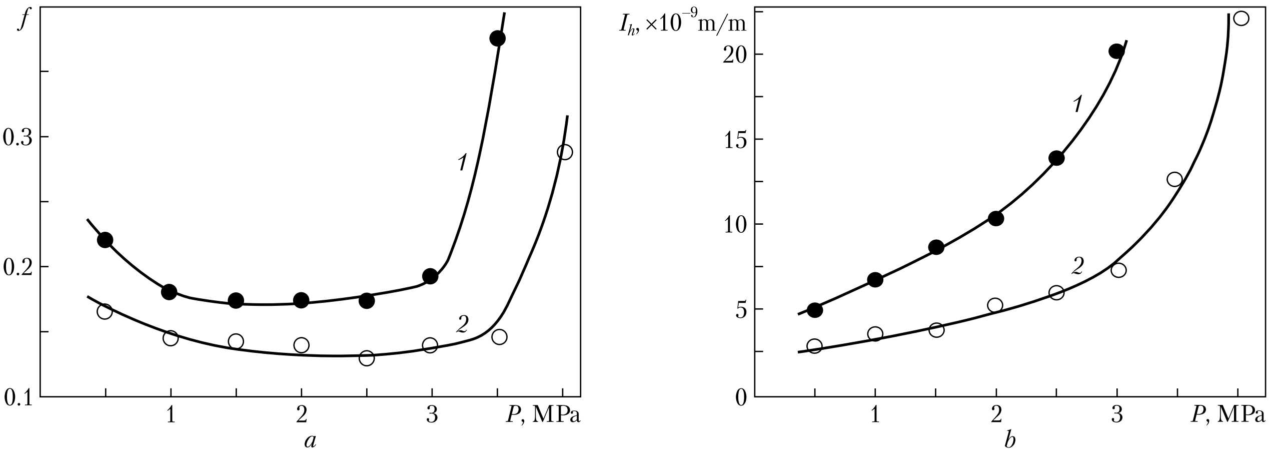


Fig. 2. Dependencies of the friction coefficient (f) and linear wear intensity (I_h) of PCMs based on aromatic polyamide (*1*) and fluoropolymer (*2*) with optimal carbon material content on load (P) during frictional interaction with steel

The developed PCM based on fluoropolymers and aromatic polyamides, filled with materials based on silicon dioxide and carbon, exhibit a high level of physicomechanical properties, with some indicators (σ_y = 285 MPa) exceeding those of most non-ferrous metals and alloys, approaching low-carbon steels. At the same time, they have a density 2—3 times lower (ρ = 2200 kg/m^3). In terms of thermophysical properties, they are among the most thermally stable polymer materials, with an active destruction temperature starting at around 365 °C, allowing the use of unloaded components made from these PCMs at such temperatures. Under load, the operating temperature of components made from these PCMs decreases to 300 °C. Regarding tribological properties, when in frictional interaction with steel, it has been established that components made from these PCMs can operate without lubrication at loads up to 2.5 MPa while maintaining a high level of reliability and durability.

Based on the conducted studies, it can be stated that the developed PCMs based on fluoropolymers and aromatic polyamides possess better properties than most existing counterparts. Consequently, using components made from these materials significantly improves the reliability and durability of frictional units, particularly in aerospace and rocket-engineering applications.

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ПОЛІМЕРНІ КОМПОЗИЦІЙНІ МАТЕРІАЛИ СПЕЦІАЛЬНОГО ПРИЗНАЧЕННЯ ДЛЯ АВІАЦІЙНОЇ ТА КОСМІЧНОЇ ПРОМИСЛОВОСТІ

Вступ. Розвиток авіаційної та космічної промисловості сприяє не тільки створенню сучасних літаків, ракет та космічних апаратів, а й позитивно впливає на суміжні галузі промисловості.

Проблематика. Однією із основних вимог до продукції авіаційної та космічної промисловості є високий рівень її надійності та довговічності, що обумовлено постійною взаємодією із людьми та досить високою собівартістю виготовлення й експлуатації. Найбільш актуальним це є для сучасних літаків, ракет та космічних апаратів, які експлуатуються при більших швидкостях, температурах, навантаженнях тощо, ніж попередники. Тому підвищення надійності й довговічності у роботі продукції авіаційної та космічної промисловості є актуальним напрямком.

Мета. Підвищити надійність та довговічність основних вузлів ракето-космічної техніки за рахунок заміни матеріалів, з яких вони виготовлені, на власні інноваційні розробки.

Матеріали й методи. Об'єктами досліджень були полімерні композиційні матеріали на основі фторполімерів та ароматичних поліамідів, які наповнені дисперсними матеріалами на основі діоксиду кремнію та вуглецю.

Результати. Розроблено склад та технології переробки у вироби полімерних композиційних матеріалів на основі фторполімерів та ароматичних поліамідів. Встановлено, що за рівнем міцності (до 285 МПа) вони перевищують більшість кольорових металів, їніх сплавів і низьковуглецевих сталей, маючи при цьому низьку густину (до 1400 кг/м^3). За теплофізичними властивостями вони належать до найбільш термостійких матеріалів на основі полімерів (не підлягають термічному розкладанню до температур +365 °С). Показано, що деталі із розроблених матеріалів можуть працювати у вузлах тертя без змащування у нормальному режимі роботи при навантаженнях до 2,5 МПа.

Висновки. Розроблено полімерні композиційні матеріали на основі фторполімерів та ароматичних поліамідів з високим рівнем властивостей, деталі з яких значно покращують рівень надійності та довговічності сучасних літаків, ракет і космічних апаратів.

Ключові слова: полімерні композиційні матеріали, фторполімери, ароматичні поліаміди, фізико-механічні властивості, тертя, зношування, авіаційна та космічна промисловість.