https://doi.org/10.31891/2307-5732-2025-359-64
УДК 678.049

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CURRENT STATUS AND PROSPECTS OF THE APPLICATION OF KEVLAR (ARAMID) FIBERS IN POLYMER COMPOSITES FOR 3D PRINTING

The relevance of the use of Kevlar (aramid) fibers in polymer composites for 3D printing technologies is due to the need to create high-strength, lightweight and impact-resistant structures that are able to operate under cyclic and dynamic loads. Given the rapid development of extrusion technologies for additive manufacturing (FFF/FDM), there is a growing need to use composite materials with increased performance characteristics that cannot be provided by traditional thermoplastics. Kevlar fibers are characterized by high specific strength, low density, heat resistance, fatigue resistance and the ability to effectively absorb impact energy. Therefore, they are considered one of the most promising reinforcing components in the structure of polymer composites for 3D printing. The article analyzes the current state of development and application of polymer composites reinforced with chopped and continuous Kevlar fibers, considers the features of the fiber-matrix interfacial interaction, technological compatibility with ABS, ASA, polyamides, technical thermoplastics and engineering polymer systems, and also analyzes the mechanical, tribological and operational characteristics of Kevlar composites. Special attention is paid to the consideration of commercial materials, laboratory research and the latest technological solutions in the field of FDM/FFF printing with aramid fiber reinforcement. It is shown that existing industrial filaments mostly contain short fibers, while the technologies for introducing continuous Kevlar threads remain limited. Promising development directions are summarized: the creation of hybrid composites, the use of coextrusion technologies, the development of pellet-based mixtures composites) and optimization of fiber orientation structure to increase the strength of 3D printed parts.

Keywords : *Kevlar (aramid) fibers, composites, polymers, FDM, 3D printing, reinforcement.*

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СУЧАСНИЙ СТАН ТА ПЕРСПЕКТИВИ ЗАСТОСУВАННЯ КЕВЛАРОВИХ (АРАМІДНИХ) ВОЛОКОН У ПОЛІМЕРНИХ КОМПОЗИТАХ ДЛЯ 3D-ДРУКУ

Актуальність застосування кевларових (арамідних) волокон у полімерних композитах для технологій 3D-друку зумовлена необхідністю створення високоміцних, легких та ударостійких конструкцій, які здатні працювати в умовах циклічних і динамічних навантажень. З огляду на стрімкий розвиток екструзійних технологій адитивного виробництва (FFF/FDM) зростає потреба у використанні композитних матеріалів із підвищеними експлуатаційними характеристиками, які неможливо забезпечити традиційними термопластами. Кевларові волокна вирізняються високою питомою міцністю, низькою густиною, термостійкістю, стійкістю до втоми та здатністю ефективно поглинати енергію удару. Тому вони розглядаються як один із найперспективніших армуючих компонентів у структурі полімерних композитів для 3D-друку. У статті проаналізовано сучасний стан розроблення та застосування полімерних композитів, армованих рубаними та безперервними кевларовими волокнами, розглянуто особливості міжфазної взаємодії волокно–матриця, технологічну сумісність з ABS, ASA, поліамідами, технічними термопластами та інженерними полімерними системами, а також проаналізовано механічні, трибологічні та експлуатаційні характеристики кевларових композитів. Окрему увагу приділено розгляду комерційних матеріалів, лабораторних досліджень та новітніх технологічних рішень у сфері FDM/FFF-друку з армуванням арамідним волокном. Показано, що існуючі промислові філаменти здебільшого містять короткі волокна, у той час як технології введення безперервних кевларових ниток залишаються обмеженими. Узагальнено перспективні напрями розвитку: створення гібридних композитів, використання коекструзійних технологій, розроблення гранульованих сумішей (pellet-based composites) та оптимізація орієнтаційної структури волокон для підвищення міцності 3D-друкованих деталей.

Ключові слова: *кевларові (арамідні) волокна, композити, полімери, FDM, 3D-друк, армування*

Стаття надійшла до редакції / Received 23.10.2025
Прийнята до друку / Accepted 15.11.2025

Introduction

The widespread introduction of additive technologies, in particular FDM/FFF 3D printing methods, has led to a growing interest in the creation of polymer composite materials capable of providing better performance than traditional thermoplastics [1]. At the current stage of development of additive manufacturing, 3D printing is actively moving from the manufacture of demonstration samples and prototypes to the production of functional elements that must withstand significant mechanical loads [2]. This applies to both elements of mechanisms and parts of transport systems, protective housings, engineering structures and technical units operating in difficult operating conditions.

Polymers such as ABS, PLA, PETG, ASA, and nylon are easy to process and have good technological compatibility with 3D printers, but their strength, stiffness, thermal stability, and impact resistance are often insufficient for use in critical structures where the material is required to perform predictably under load and to operate for a long time without failure [3]. That is why the issue of reinforcing polymer matrices is of particular importance in the context of the development of industrial 3D printing.

One of the most effective ways to improve the mechanical and operational properties of polymeric materials is the introduction of reinforcing fibers, which significantly change the matrix structure and form a composite with specified parameters of strength, stiffness and durability [4]. In this context, aramid (Kevlar) fibers occupy a special place. Kevlar, as a para- aramid material, has long been used in highly loaded composites due to its ability to absorb a significant amount of impact energy, resist fatigue failure and provide high durability under variable loads [3].

Unlike carbon fibers, which provide a significant increase in stiffness, but can degrade impact strength and promote brittle fracture, Kevlar fibers form a material with more balanced properties [1]. They combine lightness, high specific strength, moderate flexibility and the ability to perceive impulse loads without the formation of catastrophic cracks. The unique structure of Kevlar fibers based on para-oriented aromatic polyamide chains provides high crystallinity, the presence of strong intermolecular bonds and stability under significant mechanical stresses [2]. Due to this, they are a promising component for polymer composites used in products manufactured by the 3D printing method, and make it possible to create structures capable of withstanding high cyclic, shock or combined loads while maintaining low mass.

As the level of application of additive technologies in industry is constantly increasing, it is urgent to develop materials that would combine technological compatibility with FDM/FFF printing and the ability to long-term operation without degradation of mechanical properties. It is Kevlar fibers that can provide such synergy, which causes increased interest in their use in modern polymer composites for 3D printing [4].

Research object and methods

The object of the study is polymer composite materials reinforced with Kevlar (aramid) fibers, intended for use in FDM/FFF 3D printing technologies. The research methods are based on the analysis of modern scientific publications, technical data of filament manufacturers, open experimental materials, as well as the generalization of the results of laboratory studies of the influence of Kevlar fibers on the strength, stiffness, impact strength and tribological parameters of 3D printed composites.

Setting the task

The purpose of this study is to summarize the current state of development and application of polymer composites reinforced with short Kevlar (aramid) fibers in FDM/FFF 3D printing technologies. To achieve this goal, it is necessary to solve the following tasks: analyze the physical and mechanical properties of short Kevlar fibers and their compatibility with polymer matrices such as ABS, ASA, polyamides and other technical thermoplastics; consider industrial and experimental examples of composites based on Kevlar fibers; assess the influence of the content, length and distribution of short fibers on the strength, impact and operational characteristics of 3D printed parts; determine the technological limitations of FDM/FFF printing with Kevlar-containing composites and establish promising directions for their further development.

Results and their discussion

The use of short Kevlar (aramid) fibers in polymer composites for FDM/FFF 3D printing technologies is one of the most promising areas of development of modern materials for additive manufacturing. Kevlar microfibers with a length of 0.2–1.0 mm are actively integrated into thermoplastic matrices, providing a significant increase in impact strength, crack resistance and energy absorption capacity. These effects are confirmed by numerous experimental works demonstrating a significant increase in the mechanical stability of FDM-printed parts when short fibers are introduced even in low concentrations [5]. Unlike continuous reinforcement technologies, the use of short fibers does not require a change in the design of the print head, which makes such composites compatible with most industrial FDM systems.

The introduction of short aramid fibers into the polymer matrix has a clearly pronounced positive effect on the impact strength and behavior of the material under cyclic loads. This is due to the micromechanisms that are formed in the "fiber–matrix" zone: reinforcing fibers dissipate deformation energy, preventing rapid crack propagation . Studies of the behavior of fibers in polymer melts confirm that aramid fibers are characterized by high resistance to rupture, significant energy consumption of fracture and high intermolecular structural stability [6]. A significant influence on the properties of composites is the nature of the interaction of the fiber surface with the polymer. Due to the specific structure of Kevlar, consisting of para-oriented aromatic polyamide chains, the fibers have a microfibrillar structure and high crystallinity. This contributes to the formation of mechanical engagement between the fiber and the polymer. It is these microstructural features described in [7], which prove that aramid fibers are able to effectively dampen local mechanical stresses that arise in thermoplastics during loading.

Compared to other types of short fibers (glass fiber or carbon fiber), Kevlar fibers have significantly higher impact strength and better energy absorption capacity. This is reflected in [8], where it is stated that the addition of chopped aramid fibers to the polymer matrix increases the impact strength of FDM products by up to 150%, while reducing the brittle nature of the fracture. In addition, the density of Kevlar fibers is lower than that of glass fiber or carbon fiber, which allows the creation of lightweight structures with high performance characteristics.

Improved interlayer adhesion is another important effect of using short Kevlar fibers. During layer-by-layer molding, the fiber structures are partially transferred between adjacent layers, creating micro-reinforcing bridges that increase delamination resistance and improve part integrity. This is especially important for materials prone to delamination, such as ABS and ASA.

The effectiveness of reinforcement also depends on the viscosity of the matrix and the extrusion conditions. The highest efficiency of introducing short aramid fibers is characterized by polymers of medium and high viscosity - ABS, ASA, polyamides. PLA, on the contrary, demonstrates weaker interaction due to insufficient wettability of the fiber surface. According to the studies presented in [6], amorphous thermoplastics with stable rheological characteristics form the most optimal reinforcement structure in FDM printing.

Table 1 shows the technical characteristics of polymer composites with short Kevlar fibers [5-8].

Table 1

Technical characteristics of polymer composites with short Kevlar fibers

№ n/a	Indicator	ABS-Kevlar	ASA-Kevlar	Nylon-AF (aramid filled)
1	Kevlar content, %	5–15	5–10	3–12
2	Tensile strength, MPa	40–55	38–50	60–75
3	Impact strength, kJ/m²	25–45	30–55	18–30
4	Density, g/cm³	1.05–1.12	1.07–1.14	1.05–1.10
5	Elongation at break, %	3–8	4–10	6–12
6	Operating temperature range, °C	–20…+85	–25…+90	–30…+120

The effectiveness of reinforcing polymer compositions with short Kevlar fibers is largely determined by the quality of the interfacial interaction in the matrix-fiber system. It is known that aramid fibers are characterized by low surface energy, which makes it difficult to wet them with polymer melts, especially in non-polar thermoplastics. This can lead to the formation of microvoids, weak zones and a decrease in the mechanical integrity of products. Analysis of the results of the studies presented in [9] shows that the problem of weak adhesion is characteristic of many polymer matrices, but it can be partially compensated by optimizing the printing temperature regimes and choosing polymers with more pronounced polarity.

Stronger fiber-matrix interactions are observed in polyamides, where amide groups provide increased adhesion. Studies of interfacial interaction mechanisms in polyamide and ABS composites indicate that, despite the natural chemical inertness of aramids, a sufficient level of cohesion can be achieved due to micromechanical engagement and fiber orientation during extrusion. Studies of orientation processes in FDM composites [10] confirm that short fibers align along the direction of melt flow in the nozzle, which creates local reinforcing channels that significantly increase the strength in the longitudinal direction of printing.

At the same time, the fiber orientation causes structural anisotropy of the products, since the reinforcement efficiency is lower in the transverse direction. This is confirmed by experimental works, which analyzed the influence of printing trajectories, cooling rate and type of infill patterns on the orientation of short fibers. According to the results of [10], increasing the extrusion speed and decreasing the nozzle temperature contribute to an increase in the degree of fiber orientation, which, however, can reduce interlayer adhesion due to the increase in the temperature difference between the extruded layer and the previous one.

The rheological characteristics of the polymer melt play a key role in forming a uniform distribution of short Kevlar fibers. Studies conducted by the authors of [11] demonstrate that an increase in the content of short fibers in thermoplastics significantly increases the viscosity of the melt, reduces the relaxation rate and changes the flow mechanism. Even at concentrations of 3–5%, a significant increase in shear resistance is observed, which requires adjustment of the printing temperature regimes and an increase in the nozzle temperature by 10–20 °C to ensure extrusion stability. At higher concentrations (above 12–15%) there are possible fluctuations in the feed and the risk of partial nozzle clogging.

An important feature of the rheological behavior is that short Kevlar fibers not only increase the viscosity, but also affect the formation of the microstructure of the layers during the cooling process. Most of the internal defects in FDM products are formed precisely because of the mismatch between the cooling rate and the ability of the polymer melt to adapt to the volume in which the fibers are located. Uneven cooling leads to the formation of thermal stresses, which are discharged through microcracks or local delaminations. These defects can be reduced by optimizing the platform temperature, which reduces the temperature difference between the extruded material and the previous layer.

Aramid fibers on the tribological behavior of composites deserves special attention . The studies presented in [12] show that the addition of aramid fibers reduces the friction coefficient and increases the wear resistance of the polymer, especially in contacts with significant loads and high sliding speeds. This is due to the fact that Kevlar fibers have high abrasion resistance and low susceptibility to brittle fracture, which ensures the gradual and stable formation of the contact surface. This property makes composites with short aramid fibers promising for the manufacture of gears, bushings, sliding guides and other parts that work in friction pairs.

Analysis of the influence of microporosity on the mechanical properties of such composites shows that porosity is a critical factor in their strength. The presence of short fibers partially prevents the formation of large pores, however, with low interfacial adhesion or excessive matrix viscosity, defects may form, which reduce the tensile strength and yield strength. Optimization of printing modes allows minimizing these phenomena, ensuring uniform material distribution and high quality of interlayers connections .

Thus, the structural, mechanical and rheological characteristics of composites with short Kevlar fibers are determined by a whole complex of factors: the chemical nature of the polymer matrix, fiber orientation, cooling rate and extrusion conditions. Proper optimization of these parameters is key to obtaining materials with high impact strength, fatigue resistance and improved tribological properties.

One of the key factors determining the operational efficiency of composites reinforced with short Kevlar fibers is the peculiarities of the formation of the microstructure during extrusion and layer-by-layer cooling. In FDM/FFF technology, the composite structure is formed under conditions of rapid cooling of the polymer melt, which significantly affects the orientation of the fibers and the nature of their interaction with the matrix. In [13], it was proven that the efficiency of reinforcement with short fibers depends not only on their volume content, but also on the length and orientation of the fibers, since these factors determine the ability of the fibers to transfer stress in the polymer matrix.

Under the action of shear loads in the nozzle, the fibers acquire a predominant orientation along the extrusion direction. This orientation forms an anisotropic structure in which the mechanical properties are significantly higher in the printing direction and lower in the transverse direction. Analysis of the effect of fiber orientation in short-fiber thermoplastic composites shows that increasing the degree of orientation increases the tensile strength along the printing vector by 25–40%, but limits the properties in the perpendicular direction. This effect is described in detail in the monograph [14], where it is shown that there is an optimal range of fiber lengths (0.6–1.0 mm) for which reinforcement is most effective.

In the context of FDM printing, the influence of fiber length is also important. Fibers that are too short (0.1–0.2 mm) are not able to carry the load, acting only as crack growth limiters . Fibers with a length of 0.4–1.0 mm are able to form micro-reinforcing "bridges" that significantly increase the strength and impact toughness. Studies conducted in [15] confirm that with increasing fiber length to a critical value, the efficiency of stress transfer from the matrix to the fiber increases, which leads to a significant increase in tensile strength and fatigue resistance.

Interlayer zones deserves special attention. During layer-by-layer formation of the FDM structure, short fibers partially protrude into the next layer, forming micro-reinforcing bonds. This phenomenon improves cohesion between layers and reduces the risk of delamination , which is one of the main problems of FDM printing. The introduction of fibers in this way creates the effect of "fiber silk" - a structure in which fibers connect layers and increase their resistance to delamination. According to [15], with the correct adjustment of temperature conditions, the interlayer shear strength can increase by 20-30%, depending on the polymer matrix.

Printing temperature regimes play a critical role in the formation of the reinforcing structure. The nozzle temperature determines the viscosity of the polymer melt, and therefore the ability of the polymer to evenly surround the fibers. The platform temperature affects the cooling rate, which determines the level of thermal stresses in the interlayer zone. Increasing the platform temperature to 80–90 °C in ABS-Kevlar composites contributes to slower cooling and increased structural integrity of the layer. A comparative analysis of the thermal resistance of composites, performed in the studies of the authors of the work [16], shows that aramid fibers retain their properties even with prolonged heating, remaining stable within the operating temperatures of FDM thermoplastics.

An important aspect is also the influence of short fibers on the probability of porosity. Due to the increase in the viscosity of the polymer melt, fibers can create local obstacles to the flow of the material, which, under incorrect extrusion conditions, leads to the formation of internal pores. However, with correctly selected printing parameters, the presence of fibers, on the contrary, limits the development of large pores, creating a finely dispersed porous structure with increased resistance to brittle fracture. This is one of the explanations for the increased impact strength of Kevlar-containing composites.

The study of the behavior of such composites under the action of loads of various nature (impact, cyclic, static) confirms that aramid fibers are effective energy-absorbing elements . Due to the high ability of fibers to stretch, the fracture of the composite occurs by a mixed mechanism - partly due to plastic deformation of the matrix, partly due to fiber stretching, which significantly increases the energy intensity of the fracture. This position is consistent with the absorption models of fracture of short-fiber polymer composites given in [13].

Thus, the microstructural and thermomechanical processes that occur in short-fiber Kevlar composites during FDM printing, determine their high impact strength, improved interlayer adhesion and increased fatigue resistance. Optimization of fiber length, extrusion temperature regimes and cooling parameters allows you to maximize the potential of aramid fibers as an effective reinforcing component.

One of the key aspects determining the durability and operational reliability of polymer composites reinforced with short Kevlar fibers is their behavior under the influence of long-term mechanical loads, thermo-frequency cycles and external factors. Studies of the processes of anisotropic fracture and plastic deformation of composites indicate that short aramid fibers are able to significantly increase the fatigue resistance of the material, maintaining a high level of strength even after a significant number of load cycles. Analysis of microstructural mechanisms of energy absorption [17] shows that reinforcement with short fibers transfers the fracture of the polymer matrix into a mixed mode, when plastic deformation of the matrix and fiber elongation are simultaneously realized, which provides a significant increase in the energy intensity of the fracture.

Kevlar fibers, due to their high heat resistance and chemical inertness, ensure the stability of the mechanical properties of composites in a wide temperature range. Composites based on ABS-Kevlar and ASA-Kevlar retain their performance within the range of –20…+90 °C, which makes them suitable for use in products that are subjected to repeated thermal cycles or operate outdoors. In polyamides, this range is much wider and reaches +120 °C, but such matrices are more sensitive to moisture. Aramid fibers, being hydrophobic, partially compensate for the negative impact of water absorption by polyamide , but cannot completely eliminate it, therefore preliminary drying of composites before printing remains a mandatory condition.

An important advantage of composites with short Kevlar fibers is a reduction in the coefficient of thermal expansion and an increase in the dimensional stability of products. In studies of surface modification of aramid fibers carried out by the authors of [17], it was shown that even subtle changes in the chemical activity or surface structure of the fibers can significantly affect their interaction with the polymer matrix. Similar processes occur in FDM printing: reinforcement with short fibers reduces internal stresses that arise after cooling the layer due to the distribution of thermal deformation over a dispersed reinforcing network.

Resistance to external environmental factors is another key characteristic that affects the long-term operation of such materials. Ultraviolet radiation, sharp temperature fluctuations, high humidity can deteriorate the properties of the polymer matrix. However, Kevlar fibers demonstrate high resistance to UV degradation, and embedded in the polymer structure they are additionally protected by the matrix. This allows composites with short Kevlar fibers to maintain their properties in external conditions for a long time, which is confirmed by data on the long-term stability of FDM composites in real operational environments [18].

During the analysis of the mechanisms of fracture of composites, it was found that the presence of short fibers contributes to the formation of a complex system of crack propagation . Instead of a single macrocrack , characteristic of pure thermoplastics, a system of microcracks is formed in composites , the energy of which is gradually dissipated by the fibers. In the zone of maximum stresses, fiber elongation occurs, which is accompanied by significant energy absorption. This mechanism confirms that short Kevlar fibers are extremely effective reinforcing elements under shock and cyclic loading conditions.

Studies of surface modifications of aramid fibers conducted by the authors [17] demonstrate that even without the use of special modification methods, short fibers are able to significantly improve adhesion due to their natural microfibrillar structure. During printing, some of the fibers are oriented perpendicular to the layers, forming microreinforcing bonds that significantly reduce the risk of delamination .

Given their operational reliability, short-fiber composites based on Kevlar can be considered one of the most promising classes of materials for creating lightweight but strong structural elements. Their impact resistance, low mass, stability in difficult temperature conditions and high resistance to degradation make them suitable for use in transportation equipment, sports equipment, device housings, as well as in protective elements that require high energy absorption capacity.

In summary, the analysis of available studies presented in [17, 18] allows us to conclude that the further development of short-fiber composites based on aramid fibers is associated with the optimization of fiber orientation, improvement of temperature regimes of FDM printing, development of new types of polymer matrices and application of methods of fiber surface modification, which can significantly improve the adhesion and distribution of fibers in the material. Such approaches open up the possibility of creating composites with improved mechanical characteristics and increased stability for a wide range of applications.

Conclusions

As a result of the review, it was found that short Kevlar (aramid) fibers are one of the most promising reinforcing fillers for polymer composites intended for FDM/FFF 3D printing. Their use allows to significantly increase the impact strength, fatigue strength, resistance to cracking and stability of mechanical properties in a wide range of operating conditions. Kevlar fibers form a microscale dispersed reinforcing structure in the polymer matrix, which effectively dampens local stresses, prevents crack progression and provides smooth fracture mechanisms, in contrast to the brittle behavior of pure thermoplastics. A generalized analysis of experimental and literature data demonstrates that the optimal content of short fibers is 5-10%, which provides the best ratio of strength, impact resistance and technological compatibility with the FDM/FFF process.

It has been proven that Kevlar reinforcement has a positive effect on interlayer adhesion and reduces the level of internal stresses that arise as a result of layer-by-layer structure formation. Stabilization of interlayer bonds helps reduce the risk of delamination and increases the reliability of printed products. Improving the tribological properties of composites, in particular reducing the coefficient of friction and increasing wear resistance, expands the scope of their application in parts operating in friction pairs or under conditions of significant cyclic loads.

Research into the technological aspects of 3D printing has shown that the effectiveness of reinforcement largely depends on the rheological properties of the matrix, the temperature -speed parameters of the process and the uniformity of the distribution of fibers in the polymer melt. Properly selected extrusion temperatures, platform heating and feed rate provide better fiber orientation, increased interlayer adhesion and minimization of internal porosity. It was found that an excess content of Kevlar fibers (>15%) can lead to deterioration of printability, increased melt viscosity and the formation of structural defects.

The evaluation of durability and operational stability allowed us to establish that composites with short Kevlar fibers retain high mechanical characteristics after long-term cyclic loads, demonstrate a low coefficient of thermal expansion and resistance to ultraviolet radiation and most chemical environments. Due to this, they are promising materials for the manufacture of critical technical elements, body parts, components of transport systems, protective elements and functional structures that require both high strength and low weight.

In summary, it can be stated that polymer composites reinforced with short Kevlar fibers form a new class of materials for additive manufacturing with an optimal combination of mechanical, tribological and technological characteristics. In further research, it is advisable to focus on modeling fiber orientation, optimizing printing trajectories, developing new types of polymer matrices, as well as creating hybrid composites containing carbon and aramid fibers to increase structural efficiency under complex loading conditions.

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